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Journal
of
The Franklin Institute
Devoted to Science and the Mechanic Arts

Vol. 201 FEBRUARY, 1926 No. 2

THE ORIGIN OF THE EARTH'S ELECTRIC AND MAGNETIC PHENOMENA.*

BY

W. F. G. SWANN, M.A., A.R.C.S., D.Sc.

Professor of Physics in Yale University.

A CERTAIN eminent mathematician who was noted for the clarity of his expositions had, on one occasion, given a careful explanation of the principles which determine the fact that some bodies are able to float. At the end of the lecture, however, a student came to him in difficulty, for he could not understand the explanation. The whole matter was expounded again, with great care, and the student went away satisfied. Next day, however, he returned to the lecturer with a new difficulty. "I perfectly understand the explanation which you gave yesterday as to why a body may float," said he, "but, I am now unable to understand why it is that all bodies do not float." It is through some such vacillation of viewpoint as to the seat of his difficulties that one who studies the causes of some of the great phenomena of cosmical physics is apt to be lead from a state of mind in which he is unable to see any cause responsible for such a phenomenon as the earth's magnetism to one in which he is unable to understand why the earth does not have a much larger magnetic field than it actually has. For, in the case of a body of the earth's size, minor agencies wholly negligible as far as ordinary laboratory experiments are

* An address delivered Friday, September 19, 1924, on the occasion of the centenary of the founding of The Franklin Institute.

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concerned become of primary importance, so that it is only by a belief in the exactness of certain facts of electromagnetism to a degree far beyond any test which can be made in the laboratory that it is possible to account for the smallness of such electric and magnetic fields as we find the earth to possess. In other words, it is the absence, and not the presence of these phenomena which constitutes the exceptional case from the point of view of what might have been expected. Nevertheless, for a curious mixture of reasons, partly psychological, the average physicist would feel happier if he could correlate the crucial phenomena as the outcome of the laws of electrodynamics in the exact form in which he has stated them than if he should have to seek their explanation in a slight departure from those laws, even though the departure should be so insignificant as to be beyond the limits of his laboratory experiments to detect directly. I shall consequently confine my attention first to the possibilities available and the difficulties encountered in seeking an explanation in terms of strict classical electrodynamic theory.

What are the broad features which it must be the object of any theory to explain?

Our earth is not a neutral body. It is coated with a layer of negative electricity of such amount that, at the surface, there is an electrical potential gradient of the order of 150 volts per metre. This potential gradient diminishes with altitude until, at an altitude of 10 kilometres, it becomes insignificant compared with its value at the surface. The potential gradient, and so the negative charge on the earth's surface, goes through fairly regular variations throughout the day and throughout the year, variations amounting to 50 per cent. or more of its value.

The atmosphere is a very feeble conductor of electricity, so that there is a continual conduction of negative electricity from the earth's surface on account of the field. The conductivity increases with altitude in such a way that its product with the potential gradient, that is the vertical conduction current density, is roughly constant with altitude change up to such altitudes as have been investigated by balloon experiments. The conductivity of the atmosphere is extremely small. A column of air an inch long, at the earth's surface, offers as much resistance to the flow of the electric current as would a copper cable of equal cross-section extending from here to the star Arcturus and back twenty

times over. Nevertheless, this small conductivity is sufficient to insure that 90 per cent. of the earth's charge would disappear in ten minutes if there were no means of replenishing the loss. The nature of this replenishment is the greatest of the outstanding problems of atmospheric electricity.

On the magnetic side we are presented with the fact that our earth is a great magnet with its magnetic axis roughly coincident with its geographic axis. Difficulties in the way of supposing the earth to be permanently magnetized arise from the fact that the temperature of the earth's interior is probably so high as to be inconsistent with the existence of such a state of magnetization. Moreover, the direction of the magnetic axis is not constant, but varies over a long period of years. Then, the magnetic elements show periodic diurnal and annual variations much smaller in amount than those of the electric field, but, nevertheless, resembling them in the nature of their periodicities.

In spite of the fact that the earth's electric and magnetic fields are by no means small, very small primary agencies would be sufficient for their explanation, in view of the large size of the earth. Thus, the replenishing current to the earth necessary to maintain the earth's charge by making up for the loss on account of atmospheric conductivity amounts to only about 1000 amperes for the whole earth. On the electrical theory of matter, according to which we believe all matter to be made up from positive and negative electrons, it turns out that a cubic centimetre of the earth contains so much positive and negative electricity that, if these amounts could be isolated and placed at two points one centimetre apart, they would attract each other with a force of a hundred million million million tons, so that the total amounts of positive and negative electricity in the whole earth are enormous. They are so large that if one-half of 1 per cent. of the positive electricity should die in a hundred million million million years, the rate of accumulation of the surplus negative would be such as to build up an electric field equal to that of the earth before the negative electricity would be carried away through the conductivity of the atmosphere at a rate sufficient to balance the rate of death of the positive electricity. I shall return later to an elaboration of this idea when we have seen reason to fear that all methods of accounting for the replenishment on normal lines have been exhausted.

The very large amounts of positive and negative electricity in the earth insure that if we could annihilate the electricity of one sign, leaving only the other, the magnetic field produced by the rotation of the earth would amount to two million million million times the magnetic field of the earth, so that even though both signs of charge are present, a very small difference between the fields of equal and opposite charges moving with the same velocity would give rise to a residual comparable with the earth's magnetic field.

We shall presently return to a more detailed consideration of possibilities founded upon slight departures from the ordinary laws of electrodynamics; but, before doing so, we shall survey the attempts which have been made to account for the phenomena along less radical lines.

ATTEMPT AT EXPLANATION ALONG CLASSICAL LINES.

Replenishment of the Earth's Electric Charge.—Let us first deal with the problem of the replenishment of the earth's charge. As I have already remarked, the replenishment is necessitated by the fact that the atmosphere is a conductor of electricity so that charge is continually leaving the earth on account of the earth's electric field operating in this conducting atmosphere. The origin of the conductivity itself is a problem which has its own difficulties into which I shall not enter now, further than to say that we know the conductivity to be caused by the presence in the atmosphere of positive and negative ions, which ions have resulted from the splitting up of neutral molecules into positive and negative parts as a result of the action of certain external agencies. Prominent among these agencies are the radiations (α, β, and γ rays) emitted by the small amount of radium emanation in the atmosphere.

It is obvious that, if negative electricity is leaving our earth and positive electricity entering it in virtue of the potential gradient operating in a conducting atmosphere, any compensating stream must take place in opposition to the forces of the electric field. The theories which have been proposed divide themselves into two classes, those in which gravity is the primary agent instrumental in moving the charges against the field, and those in which the flux of the negative corpuscles towards the earth is brought about in opposition to the field through the agency of a very high velocity produced in them by some means or other.

Theories Invoking Gravitation.—As an example of the former class, we have the theory of Mr. C. T. R. Wilson, to the effect that the replenishment takes place through the agency of rain. Theoretical considerations have been thought to suggest that the raindrops should form on the atmospheric ions, and more copiously on the negative than on the positive ions, so that rain might be expected to be, on the whole, negatively charged. The charged drops, falling to earth under gravity, would do so in opposition to the electric field, and would constitute the replenishment. This theory is open to two primary objections. In the first place, while rain is charged, and to a degree probably sufficient to account for the necessary replenishment, it is found that 90 per cent. of the rain which falls is *positively* charged. Again, it appears that there are grave theoretical difficulties concerned with the possibility of condensation of water upon atmospheric ions, in the form of drops of appreciable size, so that this theory is now generally regarded as inadequate to account for the facts.

A theory which came near to being successful, and which undoubtedly plays a part in the origin of the earth's charge, is one due to Ebert. Ebert's theory, which constitutes a modification of an earlier theory due to Elster and Geitel, invokes the fact that if ionized air be passed through a fine tube, the negative ions diffuse to the walls of the tube more rapidly than do the positive ions, so that the air which emerges from the tube is positively charged. Ebert applies this to the atmospheric electric problem, by supposing that the air which is to be found in the interstices of the soil, and which is ionized by the radio-active material therein, is drawn out during the periods of falling barometric pressure, leaving an excess of negative charge on the walls of the interstices. The positive charge which emerges would be held in the immediate vicinity of the ground by the negative charge, but here Ebert invokes the aid of upward air currents, which carry it, against the field, into the higher regions of the atmosphere. The theory has been criticized on the basis that the emission of ions from the ground would be insufficient, and the upward currents too feeble. I think, however, that one of the most serious objections is to be found in a conclusion, which follows comparatively simply from theoretical considerations, to the effect that, on such a theory, it would result that, before the ascending positive charge had risen to an altitude of a kilometre

or so, it would have disappeared almost completely, devoured, as it were, by the negative charge continually fed into it from the earth below, through the medium of the conducting atmosphere.[1] We should obtain a positive charge in the atmosphere, a negative charge on the earth's surface, a conduction current and a potential gradient; but, all of these phenomena would be confined to a layer of the atmosphere about a kilometre or so in thickness. The whole of the positive charge in the atmosphere would be found in this layer, and, being equal to the negative charge on the earth's surface, since that was formerly its partner in neutrality, it would annul the field at all greater altitudes.

Certain other difficulties present themselves in the theory of Ebert, and in the precipitation theory of C. T. R. Wilson. Thus, in the case of both theories, the corresponding positive and negative charge densities would remain sensibly in the regions in which they originated, with the result that there would be no

[1] The reason is as follows: Let ρ be the density and v the velocity of the ascending positive electricity. Let X be the potential gradient, and λ the conductivity at a point in the atmosphere; and let the axis of x be taken vertically upwards from the earth's surface.

The equilibrium between the conduction and convection current at all altitudes required that

$$\rho v + X\lambda = 0 . \tag{A}$$

Poisson's equation gives

$$\frac{\partial X}{\partial x} = 4\pi\rho \tag{B}$$

so that, from (A) and (B)

$$\frac{v}{4\pi}\frac{\partial X}{\partial x} + X\lambda = 0$$

which gives

$$X = X_0 e^{-4\pi\int_0^h \frac{\lambda}{v} dx} \tag{C}$$

where X is the potential gradient at the altitude h.

Now, since λ increases with altitude and v decreases, the value of X as given by (C) is certainly less than the value obtained by substituting in it the surface value of λ/v, *viz.*, λ_0/v_0. Thus,

$$\frac{X}{X_0} < e^{-4\pi\frac{\lambda_0}{v_0}h}$$

If $\lambda_0 = 3 \times 10^{-4}$ e.s.u., and $v_0 = 100$ cm./sec., and if we put $h = 1000$ metres, we find that the value of X/X_0, at this altitude, is less than 0.02.

electric field at other parts of the earth. It is useless to invoke the winds for the transportation of the atmospheric positive charge to remote regions, for, on account of the conductivity of the atmosphere, 90 per cent. of it would disappear in ten minutes in the course of its journey. Difficulties of this kind confront any theory in which the replenishment of the charge takes place by the separation of charges at isolated places in such a manner that the complementary positive and negative parts are to be found comparatively near together. They become much less serious if we adopt the likely hypothesis that the lower atmosphere is surrounded by the equivalent of a conducting shell. Such a shell seems necessary to account for the reflection of wireless waves around the earth, and there is strong reason to suppose its existence on the basis of our knowledge of the mechanism of the variations in terrestrial magnetism.

In the presence of such a layer, the action of a charged cloud is to set up a difference of potential between the layer and the earth, which difference of potential is handed round, as it were, to all parts of the earth, in view of the fact that the difference in potential between the earth and the layer must be the same at all places. A detailed consideration of the action of such a layer shows that, if a charged cloud is to be found at an altitude h above the earth's surface, and if H is the altitude of the conducting layer, and R the radius of the earth, the hemisphere of the earth, which is symmetrically remote from the charged cloud, would receive R/H times the number of tubes of force which it would receive in the absence of the layer, and h/H times the number which it would receive if the charge on the earth and the charge on the cloud were pasted uniformly over the earth and atmosphere, respectively. Thus, if rain should fall from a cloud at an altitude of 5 kilometres, and if the effective altitude of the conducting layer were 50 kilometres, the average contribution to the potential gradient on the hemisphere symmetrically remote from the cloud would be one-tenth of what it would have been if the charges had been uniformly distributed over the earth and atmosphere, and over a hundred times as great as it would have been in the absence of the conducting layer. By the aid of such a conducting layer, we thus see how every centre of separation of charge, such as a rainstorm, can pay a contribution, positive or

negative, as the case may be, to the general potential gradient at every part of the earth.[2]

However, even though difficulties attending the localization of the potential gradient be removed by the postulation of the conducting layer, there yet remain the others of which we have spoken, and which are sufficiently severe to make it improbable that the phenomena of the Ebert theory can figure as the main causes responsible for the earth's charge.

Corpuscular Theories.—Turning now to theories in which the replenishment of the charge comes about by the agency of high-speed electrified corpuscles shot into the earth, the first of these was proposed by G. C. Simpson. In this theory it was supposed that the sun emitted negative and positive corpuscles of high-penetrating power. The former were supposed to pass right through our atmosphere and charge the earth, while the latter were of less penetrating power, and were caught in the atmosphere. In this way, the earth would continually receive negative, and the atmosphere positive, charge. The ordinary processes of atmospheric conduction, would, moreover, cause a continual conduction of electricity between atmosphere and earth, so that a steady state would be reached when the amount of neutralization of charge by this latter process just balanced the charging effect due to the influx of the corpuscles. This theory requires that we suppose the existence of corpuscles of penetrating power so great that they could pass through the whole of the earth's atmosphere, which is comparable in absorbing power with a column of mercury about 76 cm. high. The greatest range which has been observed in air, for the β-rays of radium, is about 7 or 8 metres. Electrons having a velocity 99 per cent. of that of light can travel through only 1.3 cm. of aluminum, which is equivalent in absorbing power to about 10 metres of air at atmospheric pressure.

[2] That the precipitation theory called for the existence of a high conductivity in the upper atmosphere was realized by C. T. R. Wilson. It may be remarked, moreover, that this action of the conducting layer minimizes slightly that objection to the Ebert theory which is founded upon the impossibility of the positive charge reaching altitudes greater than a kilometre or so. For even such a small separation in the region of replenishment makes its own small contribution to the potential gradient at other places, through the medium of the conducting layer, and the contributions in these places will be of perfectly normal type, the variations with altitude being determined only by the nature of the variation of conductivity with altitude, and in such a manner as to keep the vertical conduction current density independent of altitude.

Although, according to electromagnetic theory, the velocity of light represents the maximum velocity which a corpuscle can attain, one must guard against the supposition that, because corpuscles with velocity 99 per cent. of that of light have ranges of only 10 metres in air, no corpuscles can have ranges much greater than this. For, electromagnetic theory shows that corpuscles with velocity even 99 per cent. of that of light are very far removed in their properties from those which approach that limit much more closely. As a matter of fact, the mass of a corpuscle increases with its velocity in such a way that the corpuscle must have infinite energy in order to attain the velocity of light.

We can at first sight avoid the assumption of such long ranges by assuming that a molecule of air occasionally emits a corpuscle. Then, although on the average the corpuscles will be emitted in all directions, the earth will receive some corpuscles from the atmosphere, and it will consequently charge up until the conduction current back to the atmosphere balances the corpuscular current. Practically all the corpuscles received by the earth will come from a distance comparable with the average range of a corpuscle. We can secure the necessary replenishment with as short a range as we wish, provided that we assume a sufficiently large emission of these corpuscles from each cubic centimetre. Unless we assume a large range, however, we shall encounter difficulty from another angle. Thus, suppose that the average range were 10 metres, so that practically all the corpuscles which came to the earth came from a layer comparable in thickness with this amount. At an altitude comparable with 10 metres the resultant corpuscular current would be zero, because as many corpuscles would be shot upwards from the air below as were shot downwards from the air above. The corpuscular current would, in fact, increase from a maximum at the surface of the earth to zero at this altitude, as would also the conduction current and the potential gradient.

We thus see that if we were to have an equal emission of corpuscles from each cubic centimetre of the atmosphere, and an equal reduction of range in each centimetre of path, it would be practically necessary to assume an average total range equal to the altitude to which we wished to account for a potential gradient. The same result follows if we postulate a definite emission from each *gram* of the atmosphere, for then, although

the pressure and density decrease as we ascend, the range increases in like proportion. We can escape from this unwelcome conclusion by postulating an increase of emission per gram with altitude, such as we should have if we were to imagine the emission brought about by some external radiation which was gradually absorbed as it descended. In fact, in order to obtain a constant conduction current density, it would be necessary to postulate an increase of emission with altitude, comparable with twice the required corpuscular current, within a weight of air corresponding to the average range of the corpuscles.

It may be of interest to consider the orders of magnitude involved in a theory of this kind. It turns out that if the range is assumed to be 5 kilometres, it is only necessary to suppose that about one corpuscle is emitted per second from every 200 c.c. Now we know that about 6 ions are produced per c.c. per second, so that it is only necessary to suppose that one out of 1200 of these ions is produced with the ejection of a high-range corpuscle.

We may avoid the assumption of a spontaneous emission, and provide for certain other advantages by adopting a hypothesis which bears some resemblance to the foregoing. It has been customary to suppose that our atmosphere is traversed by a very penetrating radiation coming either from the outer regions of the atmosphere, or from some cosmical source such as the sun. This supposition has been invoked to account for the production of ions which is known to occur in a closed vessel freed as far as possible from radio-active air, even after due allowance is made for such gamma radiation from the soil as may penetrate the walls of the vessel. For reasons, the details of which I need not enter into, it has been supposed that this radiation is a form of gamma radiation, but of a type much more penetrating than the radiation ordinarily observed from radium. Now gamma-rays possess the power of ionizing, *i.e.*, of ejecting electrons from a gas through which they pass, and the nature of their action is such that the ejected electron is sent out almost entirely in the direction of the gamma-rays.

We may thus expect that such a radiation coming from above will eject electrons from the air, and these will travel certain distances in a downward direction before coming to rest. Those electrons which are shot out within striking distance of the earth will reach it and charge it. Their places will be taken by other

electrons, which have been shot out from layers above, and become absorbed before reaching the earth. One advantage possessed by this type of corpuscular theory is that it invokes, for the production of the corpuscles, an agency which is already recognized for other reasons, and another advantage lies in the fact that no artificial adjustments of the theory are necessary in order to provide for a conduction current which is practically independent of altitude.

Further, on submitting the theory to calculation, we arrive at magnitudes for the quantities involved which are by no means unreasonable. Thus, if we assume that only three high-speed corpuscles are emitted per c.c. per second, a number comparable with that which the penetrating radiation is supposed to eject, it is only necessary to assume that these corpuscles have a range of 9 metres in air in order to account for the replenishment of the earth's charge.[3] We shall presently see that, for reasons concerned with the ionization which would be produced by the corpuscles, it is desirable to endow them with a range greater than 9 metres; but, for the mere requirements of the replenishment of the earth's charge, an average range of 9 metres is sufficient.

Objections to Corpuscular Theories.—I now turn to the two main objections which may be raised against all forms of corpuscular theories. The first of these comes from failure to detect any charging effect on an insulated body exposed to the corpuscles. If corpuscles are being shot into the earth from above, an insulated mass of metal should gradually acquire a charge from the corpuscles which enter it, unless, indeed, the corpuscles are so penetrating as to pass right through it. A fairly thick mass of metal is necessary if the test is to be of value, since corpuscles which have passed through the earth's atmosphere, the equivalent of 76 cm. of mercury, will not show very much absorption in passing through a few additional centimetres of metal. I tried an experiment of this kind in 1915, but failed to find any charging effect of the type sought. More recently, von Schweidler has sought such a charging effect without success. I have always felt that my own experiments, which were done with a copper bar about 25 cm. long and 5 cm. in diameter, placed vertically, should

[3] A theory identical with that here given was developed, quite independently, by von Schweidler, somewhat later than the writer's original publication.

be repeated with a larger mass of metal, and Schweidler's experiments were done with a still smaller mass of metal. However, if we should find that a sphere of metal, let us say a metre in diameter, would experience no charging effect, any theory which attributes the replenishment of the charge to influx of corpuscles would be faced with serious difficulty.[4]

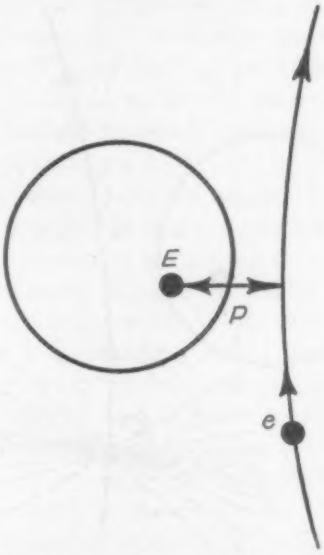
The difficulty is not insurmountable, however, if one adopts the last of the views to which I have referred, in which the ejection of the corpuscles from the molecules of air is brought about by exceptionally hard gamma-rays from above. For, on this view, if the *gamma-rays* are sufficiently penetrating to pass right through the metal, they will eject corpuscles from the bottom of the mass as well as inject them at the top. A simple calculation shows that, provided the intensity of the gamma radiation does not alter in passing through the metal, all that is necessary in order to conclude that as many electrons would be shot out of the bottom of the mass as were shot in at the top, is the assumption that the ratio of the numbers of corpuscles shot out per c.c. of air and metal is equal to the inverse of the ratio of the average ranges of a corpuscle, in air, and in the metal. This assumption is entirely consistent with our knowledge of the laws pertaining to the action of gamma-rays and the passage of corpuscles through matter.

The second great objection, and perhaps the most serious objection, at first sight, to any corpuscular theory, is the fact that we might expect the passage of high-speed corpuscles through the atmosphere, on their way to the earth, to be accompanied by a much greater ionization than is observed. The situation is this: The corpuscular current necessary to balance the atmospheric electric current amounts to an influx of 1500 corpuscles per square

[4] Since this address was delivered, I have carried out, under the auspices of the Bartol Research Foundation of The Franklin Institute, another experiment for the purpose of testing the existence of a corpuscular radiation. The mass in which absorption was sought was a cylinder of copper 19.3 cm. high and 20.5 cm. in diameter. The experiments which were carried out at Kew Observatory, England, and at Trondhjem, Norway, will be described in the near future in the JOURNAL OF THE FRANKLIN INSTITUTE. It will suffice to record at this time that the corpuscular absorption by the cylinder was less than 1 per cent. of what it would have been if there had been a vertical downward stream of such amount as would have ensured replenishment of the earth's charge and the whole of the portion of this stream corresponding to the cross-section of the cylinder had been absorbed by the copper.

centimetre per second. Now we know that an electron approximating in velocity to that of light produces about 40 ions per centimetre of its path, so that, in each cubic centimetre, we might expect ions to be produced to the extent of about 60,000 per c.c. per second, whereas experiment shows that they are only produced to the extent of one-ten-thousandth of this amount. In order to see how we may escape this difficulty, it may be of interest to probe a little more closely the mechanism of the ionization.

FIG. 1.

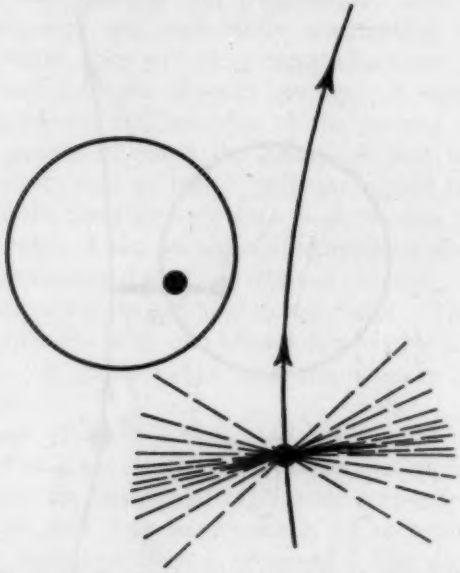


Absence of Ionization by Corpuscles with Velocities Approximating That of Light.—Suppose E (Fig. 1) is an electron in an atom, and that another electron e, which I shall distinguish by calling it a corpuscle, approaches the atom. The corpuscle will start to repel the electron as it approaches, and will continue to do so as it recedes, with the result that the electron receives energy, the momentum which it acquires being more or less in a direction perpendicular to the line of flight of the corpuscle. The greater the velocity of the corpuscle, the shorter the time during which the electron has opportunity to receive momentum from it. The efficiency of the corpuscle as regards its power to hurl the electron out of the atom thus diminishes with increase of its velocity, and would, as a matter of fact, become zero if the corpuscle could

attain an infinite velocity. The velocity of the corpuscle cannot attain a value greater than that of light, however, and, as regards the above effect, there is not very much reduction in ionizing efficiency for an increase of velocity from, say, 95 per cent. of that of light, where the ionization has been measured, to the velocity of light itself.

As the velocity of light is approached, however, another phenomenon comes in. The field of the corpuscle does not remain

FIG. 2.



uniformly distributed. According to known electromagnetic laws, its lines of force close up more and more into its equatorial plane, as indicated by the broken lines in Fig. 2. The time which the corpuscle has for acting effectively on the electron is therefore reduced still further on this account; but, the intensity of the action during that time is increased; and, it turns out, as has been shown by Bohr, that, if we take nothing else into consideration, the energy communicated to the electron by the passage of the corpuscle will be unaffected by this concentration of the lines of force.

There is one other very important consideration which we must take into account, however. If an electron receives even a

small velocity in a very short time, it is known that it will radiate a large amount of energy. Its sudden start results in a violent jerk in the æther. On submitting this matter to calculation it turns out that, even if we should wish to give to an electron but a small amount of energy, in an infinitesimal time, it would be necessary to pay a sort of tax, of an infinite amount of energy, in the shape of radiation. Now the more nearly the corpuscle approaches the velocity of light, the more suddenly does it communicate to the electron such energy as it imparts. Without entering too greatly into details, we may describe the situation as follows: In the case of a corpuscle moving with a velocity approximating that of light (say 95 per cent. of the velocity of light), but not so closely as to involve these radiation considerations, it turns out that the corpuscle must approach an electron of an oxygen atom within 0.7×10^{-10} cm., in order that it shall be able to eject that electron from the atom. If the minimum distance of approach is less than this amount the energy imparted to the electron will be greater, if it is more, the energy imparted will be less. It is, however, possible to assign to the corpuscle a velocity so high that, irrespective of the distance of approach, if we should suppose it to transmit to the electron an amount of energy corresponding to the ionization potential of oxygen (15.5 volts), we should lead ourselves to the impossible conclusion that the electron's acceleration would be so large that the energy radiated by it in acquiring its velocity would be greater than the work done on it by the corpuscle. Thus corpuscles having the velocity in question, or any higher velocity, would be unable to eject an electron from an atom of oxygen, the more easily ionizable of the two main constituents of the atmosphere. When we work out this velocity, we find that it comes out as only 45 metres per second less than the velocity of light.[5] In spite of the very close approximation of the velocity to the velocity of light, the value found happens to be exactly the velocity which Birkeland has found it necessary to assign to solar corpuscles if the bending which these corpuscles suffer in the earth's magnetic field is to be consistent with their accounting for the aurora.[6]

[5] W. F. G. SWANN: "The Absence of Ionization by Electrons with Speeds Comparable with That of Light," *Phil. Mag.*, 47, pp. 306–319, 1924.

[6] K. BIRKELAND: "The Norwegian Aurora Polaris Expedition, 1902–1903," Vol. i, Section 2, p. 596.

Corpuscles of lower speeds would suffer too large deviations in the field to permit of their accounting for the facts. The diminution of bending, resulting from approximation of the velocity to that of light, results not so much from the direct influence of high speed as from the increase in the mass of the corpuscle which approximation to the velocity of light implies. It is, of course, a fact that, if the present theory were true, it would lead to the conclusion that Birkeland's corpuscles could not ionize at all, so that they could not well account for the aurora; but it is now generally believed that the aurora is not caused by negative electrons, and the comparison with Birkeland's conclusions is only cited to show that, in invoking speeds only 45 metres per second below that of light, one would not be doing anything more drastic than has been already done in other branches of the subject. It may perhaps be worth while pointing out that closeness of approximation to the conditions pertaining to the velocity of light is not well symbolized by closeness of approximation of v to c; for, as regards the energy of a corpuscle, for example, there is an infinite range from that corresponding to v less than c by 45 metres per second, and $v = c$.

As a special aspect of the above comparison with Birkeland's data, it may be of interest to point out that, if an electron were shot from infinity into our atmosphere—in the equatorial plane, for example—it would not reach the earth, but would be turned back into space by the earth's magnetic field, unless it had a velocity nearer to that of light than the velocity which we have calculated as sufficiently great to insure absence of ionization. Indeed, with this velocity (45 metres per second below the velocity of light) the corpuscle would not succeed in approaching nearer to the earth than about eight times the earth's radius.[6]

ORIGIN OF THE EARTH'S MAGNETIC FIELD.

I have already referred to the difficulties inherent in any assumption that the earth is a permanent magnet in the ordinary sense of the term; and, it is difficult to escape the desire which has been felt by many to seek in the earth's rotation the primary origin of its magnetic state. A rotating charged body possesses a magnetic field; but the earth's charge is a hundred million times too small to produce, by its rotation, a magnetic field comparable with that of the earth, and such a magnetic field as it does produce is quite different in character from the earth's magnetic field.

I have already referred to the enormous magnetic field which would be produced by the earth's rotation if all of the electricity of one sign could be annulled. Now if we could regard the earth as two superposed spheres, one of positive electricity and the other of negative, and if the two spheres could have slightly different diameters, we should obtain a magnetic field as a result of the combined rotation of the pair because the oppositely directed magnetic fields due to the two kinds of electricity would not balance completely, since the magnetic field due to a rotating charged sphere at a point in space depends upon the size of the sphere as well as upon the total charge. This was pointed out by Sutherland many years ago, and it is an astonishing fact that it is only necessary to assume a difference in the diameters of the two spheres amounting to about 2.4×10^{-10} cm., *i.e.*, to about one-fiftieth of the diameter of a single atom, in order to account for a magnetic field comparable with that of the earth. Moreover, since two concentric spherical distributions of charge give rise to the same fields at external points regardless of the relative sizes of the spheres, the fields of these two spheres which symbolize the earth will balance completely at external points. Unfortunately, this will not be the case at internal points, however; and, indeed, at internal points near the surface the electric field would be of the order one thousand million volts per centimetre.

There are a number of causes which would operate in some degree towards producing separation of charges such as would give rise to a magnetic field as a result of the earth's rotation. Thus, it is customary to suppose that, in a solid, a large proportion of the electrons are not bound in the atoms but are free to roam about in the interstices between the molecules in very much the same way as the molecules of air fly about between the leaves of a tree. Owing to the centrifugal force of the earth's rotation, these electrons will tend to be thrown outwards. This tendency will be resisted by the attraction of the positive electricity which they would leave behind. Still there will be a small tendency in this direction; and, as a result of the rotation of this system in which the charges have been displaced, we should obtain a magnetic field. However, on submitting the matter to calculation, it turns out that the field so obtainable amounts to only 10^{-23} of the earth's magnetic field, and is, moreover, of a type differing widely from it.

Again, owing to the earth's gravitation, the electrons will tend

to move towards the centre. Apart from sign, this leads to the type of displacement postulated in Sutherland's theory; but, when we work out the magnetic field, we find that it amounts to only 10^{-21} of the earth's field, and is, moreover, in the wrong direction.

I may refer to still another possibility. We know that the inside of the earth is hotter than the outside. Now if we have a temperature gradient in a gas, the gas will become less dense where the temperature is high than where it is low, so the electrons will tend to become less dense in the hot regions than in the colder, this tendency being resisted by the electrostatic attraction which is set up as a result of the separation. On working this case out, we find that the magnetic field resulting from it amounts to only 10^{-17} of the earth's field, although it happens to be in the right direction.

There are a number of other possibilities somewhat similar to those which I have discussed; but, on submitting them to calculation, they all lead to fields of an order of magnitude quite infinitesimal compared with the earth's field. I think we may conclude, as a general rule, that it is practically hopeless to seek an explanation of the earth's magnetism on the basis of the rotation of charges which have been separated against electrostatic attraction, since the mechanical forces necessary to produce the required separation must be, in all cases, enormous.

We have reason to believe that the magnetic characteristics of atoms arise from the revolutions of electrons in orbits within them. Such a rotating system constitutes a gyroscope which tends to turn its axis parallel to the earth's axis of rotation. Thus, if the atoms of the earth are magnetic in character we may expect a certain magnetization of the earth as a whole as a result of its rotation. When we submit the matter to calculation, however, the most favorable assumptions yield a magnetic field for the earth only two ten-thousand-millionths of the earth's magnetic field.

It has been thought that the earth might be magnetized to its present state by a very weak magnetizing field, as a result of a very high magnetic permeability arising from some unknown cause. Any attempt at an explanation along these lines ignores the fact that, owing to the high demagnetizing action of the poles of a sphere, it is impossible to magnetize the sphere to such an extent that the flux through it is more than three times the flux

which would be there in the absence of the sphere, even though the permeability of the sphere were infinite.

The earth's magnetic field could be explained if we could provide for a suitable circulation of currents within its interior. Such an attempt at explanation calls, however, for an explanation of the electromotive forces wherewith to maintain the currents. Prof. H. Lamb has shown that, if a system of currents were started in a sphere of the earth's size, and the electromotive forces necessary to maintain them removed, then, on account of the large electrical inertia of the sphere the currents would take ten million years to die to one-third of their initial values in case the electrical conductivity of the material of the sphere were as high as that of copper. When we seek an explanation of the earth's magnetic field along these lines, however, we become confronted with grave difficulties, as Sir Arthur Schuster has shown, on account of the enormous currents which would be calculated by extrapolating back even over to epochs not more remote than those during which the earth's crust has been solid.

The current density necessary to account for the earth's magnetic field amounts to only about one-hundred-millionth of an ampere per square centimetre at the earth's surface on the equator. It would be explained if we could see some way in which, on account of the earth's rotation, there should be a slight difference between the angular velocities of the electricity which we regard as free (the free electrons) and the remainder which goes to make up the substance of the earth. A difference in angular velocity corresponding to one part in 7×10^{16} would be sufficient if the earth contained 10^{23} free electrons per c.c., a number not unreasonable to suppose. Such a difference could arise if, owing to tidal action, for example, the earth's velocity were diminishing, the free electrons lagging behind in the decay of the rotation until the drag due to this lag brought about a state of equilibrium. Unfortunately, when we submit the matter to calculation, we find that, in order to account for the necessary drag to provide for the earth's magnetic field, we should have to suppose the earth's angular velocity to diminish so rapidly that it would fall to zero in a day.

When we proceed to enquire in somewhat greater detail as to the effect of rotation on the relative velocities of the free electrons and the remainder of the matter, we find that the problem invites

the consideration of certain questions whose solution lies in those details which are bound up with the theory of conduction of electricity in solids, and here, indeed, a possibility for further development seems open. It is not out of the realms of possibility that we may ultimately see in the details of the thermodynamic equilibrium of free electrons in a rotating matter a means of realizing a relative motion between the free electrons and the remainder of the matter of such a kind as to provide for the earth's magnetic field without a very radical departure from the primary fundamentals of classical theory.

If, however, we feel that all of the possibilities of accounting for terrestrial magnetism along the lines of classical electrodynamics have been exhausted, we must turn our attention to the question of what modifications may be made in the classical laws with a view to securing the desired end.

THEORIES INVOKING DEPARTURES FROM THE CLASSICAL LAWS.

MODIFICATION OF FORCES BETWEEN STATIONARY CHARGES.

Many years ago, Lorentz suggested a modification of the laws of electrical attraction and repulsion with the object of accounting for gravitation. He assumed that unlike units of charge attracted each other with a force slightly greater than that with which like units repelled each other. It would result from this that two pieces of neutral matter would exhibit an attraction, and this attraction be associated with gravitation.

If, assuming that unit charges of either sign are defined so that the repulsive force between like charges, e_1, e_2 is $\frac{e_1 e_2}{r^2}$, we also assume that the force exerted by a positive charge e_+ on a negative charge e_- is $(1 + \alpha)\ \frac{e_+ e_-}{r^2}$ and the force exerted by a negative charge e_- on a positive charge e_+ is $(1 - \beta)\ \frac{e_- e_+}{r^2}$, where α and β are small positive quantities, we obtain a wider range of possibility.

This assumption would apparently give up the law of action and reaction; but this would cause no serious difficulty for reasons which I will not dwell upon now.

It would, on this hypothesis, result that a free electron in a neutral sphere would not be in equilibrium since the attraction on it due to the positive charges within would outweigh the repulsion due to the negative. It would be necessary for the sphere to

require a negative charge in order that equilibrium should be established, and it is possible to determine α so that this negative charge would be such as to give rise by its rotation to a magnetic field comparable with that of the earth. While β plays no part in determining the equilibrium of a free electron, it does play a part in determining the total force which would be exerted on the element of matter composed as it is of both positive and negative electrons; and, it is possible to determine β so that the net force on the element of matter is just such as to correspond to gravitation. The details of the calculation are given in the appendix to this article, and it will suffice to say here that, in order to account on these lines for both terrestrial magnetism and gravitation, it is necessary to have $1 + \alpha = 1 + 1.9 \times 10^{-19}$, and $1 - \beta = 1 - 1.9 \times 10^{-19} + 0.78 \times 10^{-36}$ so that both α and β are zero to within all limits of detection by laboratory experiments. We obtain by our hypothesis a volume charge sufficient to give by its rotation the earth's magnetic field; but, our modification of the law of attraction has saved us from the consequences of a very large electric field such as we should encounter on classical lines; and, indeed, the residual electrical forces have been adjusted so as to no more than satisfy the demands of gravitation.

Tempting as this view may seem, it is not without its difficulties, for modifying the laws of electrodynamics is very like modifying the constitution of a country. We may adjust matters very nicely to fit in with one set of circumstances, but we run a great danger of upsetting something elsewhere. Now so far we have spoken only of the statical forces between the charges. However, two like charges moving in the same direction or two unlike charges moving in opposite directions attract each other by virtue of their motion, quite apart from the statical forces to which I have already referred. This is really the fundamental fact which gives rise to our conception of a magnetic field. We say that the charge A, on account of its motion, produces a magnetic field, and the charge B, on account of its motion in that magnetic field experiences a force. It is this force which we are really concerned with whenever we measure a magnetic field by utilizing the forces exerted on a magnet. For, the forces on the magnet itself are ultimately traceable to the forces on the individual electrons whose motions in the molecules of the magnet give that magnet its magnetic properties.

Now, for reasons which it would take too long to give in detail here (see, however, Appendix to this article, Note 2), it turns out that if we desire to formulate a complete scheme of electrodynamics in such a manner as to conform to the requirements of the restricted theory of relativity, we must not allow ourselves to modify the law of force between statical charges without modifying that between moving charges as well, and in the same ratio. Thus if we wish to say:

(A) The force produced by a stationary unit of positive charge on a stationary unit of negative charge exceeds the force between corresponding like charges in the ratio $(1+\alpha)$ to unity, and the force produced by a stationary unit of negative charge on a stationary unit of positive charge falls short of the corresponding force between like charges in the ratio $(1-\beta)$ to unity, we must also say:

(B) In the case of the force due to a moving positive unit of charge on a moving negative unit of charge, the portion of the force depending on the motion exceeds the corresponding force for like charges in the ratio $(1+\alpha)$ to unity; and, in the case of the force due to a moving negative unit of charge on a moving positive unit, the portion of the force depending on the motion falls short of the corresponding force between like charges in the ratio $(1-\beta)$ to unity.

Now at first sight we appear to have occasion to rejoice greatly; for, the new assumptions A and B would, on their own account, give rise to the equivalent of a magnetic field. For, even in the case of a neutral rotating earth, the portions of the forces on a moving electron which result from its motion and the motion of the two kinds of electricity which compose the earth would not balance out. Our electron would experience a force which, following in our thoughts the spirit of the classical theory, we should take as evidence of the existence of a magnetic field. But, alas, our theories are now too many; for it turns out that the apparent magnetic field which we have evolved out of the assumptions A and B just cancels the magnetic field which we evolved out of the former assumptions as to modification of the statical forces between the charges (see Appendix to this article, Note 2). Of course, we can avoid the difficulty if we are willing to give up the restricted theory of relativity; but, to do this would be to

formulate a scheme of laws which would be repugnant to our experience in all other branches of physics.

MODIFICATION OF ELECTRODYNAMIC EQUATIONS.

Warned by the above unhappy ending to what seemed likely to turn out a promising theory, let us now proceed with greater caution to see in what way we can make modifications in the electrodynamic laws in a manner which, while maintaining a harmonious unity between them, leads nevertheless to the desired end. It will only be possible to give here a brief outline of the procedure adopted, and it will be necessary to reserve for a future publication the more complete mathematical details. Let us first recall what the electrodynamic laws, which it is our purpose to modify, are. These laws are summed up in the well-known equations of the Maxwell-Lorentz theory.

$$\frac{\rho \mathbf{u}}{c} = \frac{-1}{c}\frac{\partial \mathbf{E}}{\partial t} + \operatorname{curl} \mathbf{H} \qquad (1)$$

$$0 = \frac{1}{c}\frac{\partial \mathbf{H}}{\partial t} + \operatorname{curl} \mathbf{E} \qquad (3)$$

$$\rho = \operatorname{div} \mathbf{E} \qquad (2)$$

$$0 = \operatorname{div} \mathbf{H} \qquad (4)$$

$$\mathbf{F} = \left(\mathbf{E} + \frac{[\mathbf{wH}]}{c} \right) e \qquad (5)$$

In these equations, $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic fields, ρ the density and $\mathbf{u}$ the velocity of the electricity, c being the ratio of the electromagnetic to the electrostatic unit of charge. Equation (5) gives the so-called "ponderamotive" force acting on an electron of charge e and velocity $\mathbf{w}$, the understanding being that $\mathbf{E}$ and $\mathbf{H}$ in this equation refer to the electric and magnetic fields, omitting that of the electron in question. The equation of motion of the electron is obtained by equating $\mathbf{F}$ to a certain function of the motion of the electron involving a series of terms containing the acceleration and all higher time derivatives of the motion.

It is not my present purpose to use these equations other than as a nucleus on which to crystallize the discussion. One or two facts with regard to them must be observed.

(1) The equations contain implicitly the law of conservation of charge. Their form is such as to so bind the way in which charge density changes with the way in which charge moves as to ensure that the rate at which charge increases in any region of space is equal to the excess of the rate of entry over that of exit. In the technical mode of expression, the charges move so as to obey the equation of continuity. It may be remarked that this is

not a consequence of pure logic apart from the fact that the equations provide for it. Such a law is not true for everything. It is not true of the population of this country that the rate of increase of population is equal to the excess of immigration over emigration; for, some die here and some are born here. Equations (1)–(4), by implying the equation of continuity, deny to electricity the privilege of being born or of dying.

(2) Equations (1)–(4), together with a force equation obtained by equating **F** to a suitable function of the motion of the electron, are known to be consistent with the restricted theory of relativity. In other words, they are of such a form as to provide for the fact that, although an observer moving relatively to ourselves with constant velocity would measure different densities and velocities for the electricity, and different values for the electric and magnetic fields, the densities, velocities and fields which he did measure would be related by equations of the same form as those which relate our densities, velocities and fields.

(3) As is well known, it is possible to solve equations (1)–(4) in such a way as to obtain the values of **E** and **H** at any point in space when the values of ρ and **u** are assigned throughout all space for all time. Moreover, the solutions make no particular use of the *forms* of the left-hand sides of (1) and (2). We could replace $\rho\mathbf{u}$ and ρ by almost anything we pleased, say **S** and T, respectively,[7] and the solutions would give **E** and **H** in terms of **S** and T in the same form as they before gave them in terms of $\rho\mathbf{u}$ and ρ. In other words, the equations would not "know" but that **S** was a current density and T a charge density.

(4) Finally, it must be remarked that, when we solve equations (1)–(4) for **E** and **H**, the solution is of such a type that each element of charge in the whole space makes its own independent contribution to **E** and **H**. The various elements do not interfere with each other, as it were. For this reason, it would be possible, if we so choose, to speak of the fields $\mathbf{E}_+$ and $\mathbf{H}_+$ due to positive electricity and the fields $\mathbf{E}_-$ and $\mathbf{H}_-$ due to negative electricity, and to keep them quite distinct in our minds. This, in fact, forms the first step in our preparation for a generalization of the equations.

[7] The only condition restricting **S** and T is that they shall satisfy the condition $\operatorname{div}\mathbf{S} + \frac{\partial T}{\partial t} = 0$.

It will be noticed that equations (1)–(4) contain nothing about the charge but its density and velocity. The rate of change of density or of velocity does not occur in them. One is thus led to enquire whether the equations may not therefore represent only an approximation to the truth. To illustrate the spirit of this idea, suppose we consider a circle of wire carrying a current. Then, according to ordinary physical ideas, we imagine the magnetic field as produced entirely by the velocity and density of the electricity in the wire. However, the electricity also has acceleration towards the centre, and rate of change of acceleration tangential to the circle and so on. Why should it not be that even for a steady state, a steady current,[8] the acceleration, rate of change of acceleration and all the higher time derivatives give contributions to the magnetic field. If such were the case, then in the case of a current flowing in a circle, for example, we should obtain from that current when produced by a density ρ and a velocity $\mathbf{u}$ a different magnetic field from that produced by a density 0.5ρ and a velocity $2\mathbf{u}$.

Let us then proceed to generalize our equations in the spirit of the foregoing idea; but, let us first imagine two sets of equations, one for the fields due to positive and the other for the fields due to negative electricity, and let us confine our generalization to the former set. This generalization shall take the form of the addition of extra terms to $\rho\mathbf{u}$ and ρ. Now the theory of relativity has something to say as to the types of terms which we may add if we are to retain consistency with that principle. Thus, it is possible to add to $\rho\mathbf{u}$ a term which is approximately proportional to the time rate of change of $\rho\mathbf{u}$, provided we add to ρ a corresponding term which turns out to be approximately proportional to the time rate of change of ρ. Then it is possible to add to the $\rho\mathbf{u}$ expression another term which is approximately proportionate to the second time rate of change of $\rho\mathbf{u}$, provided that we add to the ρ expression a corresponding term which turns out to be approximately proportional to the second time rate of change of ρ, and so on. Moreover, it is possible to generalize each of the corresponding additions to $\rho\mathbf{u}$ and ρ by multiplying it by an invariant, that is a function of the velocity, accelera-

[8] We here limit the discussion to that for a steady state as, in other cases, even the classical electrodynamics causes the magnetic field to depend upon the acceleration and higher time derivatives.

tion, etc., which when subjected to the relativity transformation leaves its magnitude unchanged. We shall content ourselves with the addition to $\rho\mathbf{u}$ of two terms $\alpha\mathbf{P}$ and $\beta\mathbf{Q}$, the corresponding additions to ρ being αp and βq. The quantities $\mathbf{P}$ and $\mathbf{Q}$ which we choose are practically the first and second time rates of change of $\rho\mathbf{u}$, generalized, however, to provide for consistency with the restricted theory of relativity, while α and β are invariants. The actual expressions chosen for $\mathbf{P}$ and $\mathbf{Q}$ are $\mathbf{P} = k\frac{d}{dt}\rho\mathbf{u}$, and $\mathbf{Q} = k\frac{d}{dt}k\frac{d}{dt}\rho\mathbf{u}$, where $k = (1 - v^2/c^2)^{-\frac{1}{2}}$, and v is the resultant velocity. The corresponding expressions for p and q are $p = k\frac{d\rho}{dt}$, and $q = k\frac{d}{dt}k\frac{d}{dt}\rho$. Thus, as regards equations (1)–(4), for positive electricity, $\rho\mathbf{u}$ becomes replaced by $\rho\mathbf{u} + \alpha\mathbf{P} + \beta\mathbf{Q}$ and ρ becomes replaced by $\rho + \alpha p + \beta q$, while for negative electricity the equations remain unaltered. The net result of this is that, in the case of a rotating neutral mass, the $\rho\mathbf{u}$ terms cancel for the two kinds of electricity, and we are left with the equivalent of a current density $\alpha\mathbf{P} + \beta\mathbf{Q}$, and the equivalent of a charge density $\alpha p + \beta q$.

Now it turns out that, for uniform rotation, p and q are sensibly zero, in other words, there is no "apparent charge density" for uniform rotation. However, the quantities $\mathbf{P}$ and $\mathbf{Q}$ are not zero for uniform rotation. This is a very important matter; for, had p and q been finite for this case, we should have run the danger of invoking a large electric field as a necessary accompaniment to our magnetic field, and it would be no consolation to us to know that it was not due to excess of one kind of charge but to neutral matter. The terms $\alpha\mathbf{P}$ and $\beta\mathbf{Q}$ are the equivalents of current density as regards their power to produce magnetic fields. It turns out that the former is the equivalent of a radial current density and the latter of a tangential current density. It is the tangential apparent current density which is of service to us in attempting to account for the earth's magnetic field; and as far as this is concerned, we could dispense with the introduction of the term $\alpha\mathbf{P}$. We shall find this term very useful in another connection, however; but, since the magnitude which it is necessary to assign to it in that connection is so small that its influence on the magnetic field is negligible, we may confine our attention as regards the magnetic field discussions to the term $\beta\mathbf{Q}$. The velocity, acceleration, time rate of change of acceleration of a

particle in the earth depend upon the distance of that particle from the axis of rotation as well as upon the angular velocity. Thus, by a suitable choice of the invariant β, it becomes possible to control the relation between the apparent current density $\beta\mathbf{Q}$ and the angular velocity and distance from the axis of rotation; and, it readily follows from this that it is possible to control the form of the expression for the magnetic field produced by the rotating sphere as a function of the radius of the sphere and the angular velocity. It is possible to do this in such a way that the theory predicts the correct ratio of the magnetic field of the earth to that of the sun,[9] and also predicts that it would be impracticable to detect the magnetic field of a small sphere, of say 10 cm. radius, rotating at a high angular velocity, say 100 revolutions per second. These two tests must be satisfied by any theory which claims to explain terrestrial magnetism as a result of rotation.

Let us now turn to the term $\alpha\mathbf{P}$. I have remarked that the classical equations provide for the equation of continuity for electricity. They provide for the conservation of charge. It turns out, however, that the additional terms $\alpha\mathbf{P}$ and $\beta\mathbf{Q}$ in the equations for positive electricity prevent the equation of continuity from holding for positive electricity although, of course, it still holds for the negative. In other words, it results that, in the case of any motion of positive electricity other than the uniform rectilinear type, it is no longer true that the rate at which positive electricity grows in a space is equal to the excess of entry into, over exit from, that space. The electricity is required to die or to be born as a result of its motion.

Dr. G. C. Simpson [10] has mooted the question of whether the atmospheric electric current may not be provided for by a spontaneous generation of charge within the earth. Such a hypothesis as birth or death of charge runs the danger of appearing very artificial, and is apt to leave us with an uncertainty as to where we stand with regard to the meanings of our fundamentals. In the form in which we have introduced it, however, the hypothesis

[9] Since, other things being constant, the magnetic fields produced by equal spheres are proportional to the amounts of positive electricity per c.c., the density of the substance of the sphere also appears in the expression for the magnetic field produced by a rotating sphere.

[10] G. C. SIMPSON: "Some Problems of Atmospheric Electricity," *Monthly Weather Review*, 44, p. 121, 1916.

makes its appearance with perfectly definite meaning in a form consistent with and a direct outcome of the whole scheme of equations which describe the laws of the phenomena.

If we make our theory provide for a slow death of positive electricity on account of the rotation, the surplus negative electricity will accumulate until it has built up such an electric field that the rate at which it is carried away into space in virtue of the conductivity of the atmosphere results in a balance. In this way the atmospheric electric current is provided for. While both the $\alpha\mathbf{P}$ and the $\beta\mathbf{Q}$ terms contribute to the birth or death of charge for the most general state of motion, only the former term makes any contribution for uniform rotation. In order to provide for the necessary atmospheric electric current, it is only necessary to provide for a rate of death of positive electricity such as would correspond to a disappearance of one-half of 1 per cent. of the earth's mass in a hundred million million million years. Put in another form, we may say that the necessary rate of death amounts to less than one proton per c.c. per day. The value which it is necessary to attribute to the $\alpha\mathbf{P}$ term for this purpose is so small that, as already stated, it is insignificant in its effect on the magnetic field. It may be of interest to remark that, for the magnitudes of the accelerations encountered in the earth's rotation, the values which it is necessary to assign to the numerical coefficients in α and β in order to provide for the replenishment of the earth's charge and for the earth's magnetic field are such that the $\alpha\mathbf{P}$ and $\beta\mathbf{Q}$ terms amount, respectively, to only about one part in 10^{26} and five parts in 10^{19} in comparison with the main $\rho\mathbf{u}$ term.

GRAVITATION.

Gravitation becomes incorporated into the scheme in a manner almost completely analogous to that adopted in the theory of Lorentz. The equation expressing the force on an electron due to the field becomes split up into two, one for the force on a positive electron and one for the force on a negative electron. These equations are, in fact,

$$\mathbf{F}_+ = \left\{ \mathbf{E}_+ + \frac{[\mathbf{w}_+ \mathbf{H}_+]}{c} + \lambda \left(\mathbf{E}_- + \frac{[\mathbf{w}_+ \mathbf{H}_-]}{c} \right) \right\} e \tag{6}$$

$$\mathbf{F}_- = \left\{ \mathbf{E}_- + \frac{[\mathbf{w}_- \mathbf{H}_-]}{c} + \lambda \left(\mathbf{E}_+ + \frac{[\mathbf{w}_- \mathbf{H}_+]}{c} \right) \right\} e \tag{7}$$

where $\mathbf{F}_+$ and $\mathbf{F}_-$ refer, respectively, to the forces on a positive and a negative electron. $\mathbf{E}_+$, $\mathbf{H}_+$ are the fields due to positive electricity, and $\mathbf{E}_-$, $\mathbf{H}_-$ those due to negative electricity. $\mathbf{w}_+$ and $\mathbf{w}_-$ refer, respectively, to the velocities of a positive or negative electron. The quantity λ is a constant which, in its difference from unity, provides for the conclusion that the force due to given negative fields $\mathbf{E}_-$ and $\mathbf{H}_-$ on a positive electron are slightly greater than the force due to equal positive fields $\mathbf{E}_+$ and $\mathbf{H}_+$; and, the force due to given positive fields on a negative electron are slightly greater than the force due to equal negative fields. The effect of λ is of course to provide for a residual attraction between two pieces of neutral matter; and it is only necessary to make λ differ from unity by less than one part in 10^{36} in order to provide for the necessary gravitational constant. Moreover, equations (6) and (7), when taken in conjunction with equations (1)–(4) for negative electricity and the corresponding modified equations for positive electricity, are of a form in harmony with the requirements of the restricted theory of relativity.

CONCLUSION.

In the portion of this article immediately preceding, we have sketched a modification of the laws of electrodynamics which involves the addition of two terms to the current density in the field equations for positive electricity, the equations for negative electricity being left unchanged. For the magnitudes involved in the earth's motion, these terms amount at most to one part in 10^{26} and five parts in 10^{19} of the main term of classical theory. The modification provides for the correct value for the part of the magnetic field of the earth which is symmetrical about the axis of rotation. It gives the right value for the ratio of the magnetic field of the earth to that of the sun, and it ensures that the magnetic fields obtainable from bodies of laboratory size rotating at the highest attainable speeds would be immeasurable. Further, the modification provides for a slow death of positive electricity on account of rotation, a death amounting to a disappearance of only one-half of 1 per cent. of the earth's charge in a hundred million million million years. In the corresponding surplus of negative electricity freed by this process, the atmospheric electric current and the atmospheric potential gradient are provided for. Further, the theory predicts that, in the case of spheres of

laboratory size rotating with the highest attainable velocities, the generation of charge would be immeasurably small. The law of force between like and unlike charges has been modified along the lines of the theory of Lorentz in such a way as to provide for gravitation. Finally, the whole scheme of equations is of a form consistent with the requirements of the restricted theory of relativity; and, we may add that it may be generalized to a form consistent with the general theory.

It has of course only been possible to give a brief outline of the theory. Many points which will doubtless occur to the reader will be discussed more fully in the complete account which will be published later. Any attempt along such lines as we have adopted naturally invites the criticism that it is artificial. However, I think we must come to realize that the factors which determine artificiality are largely psychological. In terms of the classical electrodynamics it has turned out that the electric and magnetic fields are determined by the motion of electricity in a certain way and we are satisfied. Justification for this satisfaction lies in our familiarity with the idea rather than in any fundamental requirements of logic. Apart from previous experience, we might indeed regard it as a very remarkable thing that the charge density and the velocity are the only things which make their appearance in the electrodynamic equations. In the whole complexity of motion, velocity should enjoy no special favors in determining things, and the most natural view would be to suppose that the equations would contain terms involving the acceleration, time rate of change of acceleration, etc., and the various time derivatives of the density. To the mathematician, this would be the most likely state of affairs, and absence of such terms would seem peculiar. Indeed, the surprising thing would appear to be the smallness of such terms. Herein lies the significance of the statement made at the beginning of this article, to the effect that one is apt to be lead from a state of mind in which he is unable to see any cause responsible for such a phenomenon as the earth's magnetism to one in which he is unable to understand why the earth does not have a much larger magnetic field than it actually has. However, in spite of this viewpoint, many will undoubtedly feel that such modifications of the electrodynamic laws as we have discussed are unsatisfying. To such

we reply that if they do not like the discussion as presenting a theory of terrestrial magnetism, atmospheric electricity and gravitation, they may at least take the relative smallness of these phenomena in nature as evidence of an extreme symmetry of the electromagnetic equations for positive and negative electricity, at least as regards any generalization of the current density term which they contain and evidence of extreme equality in the forces of attraction and repulsion between corresponding unlike and like charges.

APPENDIX.

Note 1. Results of Modification of the Law of Force between Static Charges.—Let ρ_+ and ρ_- be the densities of positive and negative electricity, respectively.

The condition that a free electron in the matter shall be in equilibrium is

$$\text{grad}\,(1+\alpha)\iiint \frac{\rho_+}{r}\,d\tau + \text{grad}\iiint \frac{\rho_-}{r}\,d\tau = 0 \qquad (8)$$

where α has the significance given in the text, and the integrals are taken throughout the regions comprised by the matter.

The force on all the electricity in an element of volume dV is

$$\left[\text{grad}\,(1+\alpha)\iiint \frac{\rho_+}{r}\,d\tau + \text{grad}\iiint \frac{\rho_-}{r}\,d\tau\right]\rho_- dV$$
$$+\left[\text{grad}\,(1-\beta)\iiint \frac{\rho_-}{r}\,d\tau + \text{grad}\iiint \frac{\rho_+}{r}\,d\tau\right]\rho_+ dV \qquad (9)$$

where, in the general case, the ρ's might be functions of the coördinates. This is the quantity which the theory makes equal to the gravitational force on the element of volume dV. Thus, using (8) and (9), we have

$$\left[\text{grad}\,(1-\beta)\iiint \frac{\rho_-}{r}\,d\tau + \text{grad}\iiint \frac{\rho_+}{r}\,d\tau\right]\rho_+ dV$$
$$= \left[\text{grad}\,G\iiint \frac{D}{r}\,d\tau\right] D\,dV \qquad (10)$$

where D is the density of the matter. Now, if m_+ and m_- are the masses of a proton and an electron, respectively, and N_+ and N_- the corresponding numbers of these entities per c.c.,

$$D = N_+ m_+ + N_- m_- .$$

For a body which is sensibly neutral; or for which $N_+ - N_-$ is small compared with N_+, we consequently have

$$D = N_+ (m_+ + m_-) = \frac{\rho_+}{e} (m_+ + m_-) \tag{11}$$

where e is the electronic charge, so that, from (10),

$$\text{grad}\,(1-\beta) \iiint \frac{\rho}{r} d\tau + \text{grad} \iiint \frac{\rho_+}{r} d\tau = \left(\frac{m_+ + m_-}{e}\right) G \text{ grad} \iiint \frac{D}{r} d\tau \tag{12}$$

For (8) and (12) to be true, it is sufficient that

$$(1+\alpha)\rho_+ + \rho_- = 0 \tag{13}$$

and

$$(1-\beta)\rho_- + \rho_+ = \left(\frac{m_+ + m_-}{e}\right) GD \tag{14}$$

and these conditions are also necessary if (8) and (12) are to be true for bodies of all shapes.

From (14) and (11),

$$(1-\beta) = -\frac{\rho_+}{\rho_-}\left[1 - \left(\frac{m_+ + m_-}{e}\right)^2 G\right] \tag{15}$$

The net quantity of electricity ρ per unit of volume is,

$$\rho = \rho_+ + \rho_- \tag{16}$$

Hence, from (15) and (16),

$$1 - \beta = \left[\frac{1}{1 - \frac{\rho}{\rho_+}}\right]\left[1 - \left(\frac{m_+ + m_-}{e}\right)^2 G\right] \tag{17}$$

i.e., approximately

$$\beta = -\frac{\rho}{\rho_+} + \left(\frac{m_+ + m_-}{e}\right)^2 G \tag{18}$$

and from (13) and (16)

$$\alpha = -\frac{\rho}{\rho_+} \tag{19}$$

Since ρ_+ is given in terms of D by (11), equations (18) and (19) serve to determine α and β in terms of $(m_+ + m_-)/e$, G and ρ. The last named quantity becomes determined as the value necessary to give rise to the earth's magnetic field as a result of its rotation. The necessary value of ρ is

$$\rho = -3.0 \times 10^{-4} \text{ e.s.u.}$$

Putting $G = 6.6 \times 10^{-8}$, $D = 5.5$, and $\frac{m_+ + m_-}{e} = 0.345 \times 10^{-14}$, we readily find

$$\alpha = 1.9 \times 10^{-19}; \quad \beta = 1.9 \times 10^{-19} + 0.78 \times 10^{-38}$$

Note 2. Results of Modifications of the Forces between Moving Charges.—The classical theory gives $\mathbf{E} + \frac{[\mathbf{w}\mathbf{H}]}{c}$ for the force per unit charge on a positive electron moving with velocity $\mathbf{w}$. The classical force per unit negative charge due to the fields $\mathbf{E}_+$, $\mathbf{H}_+$ resulting from the positive charges is $\mathbf{E}_+ + \frac{[\mathbf{w}_-\mathbf{H}_+]}{c}$, and the modification which we have made in the statical forces requires that for the statical case, the force per unit charge shall reduce to $(1+\alpha)\mathbf{E}_+$, which suggests that the factor $(1+\alpha)$ be applied to the $\mathbf{E}_+$ in the expression $\mathbf{E}_+ + \frac{[\mathbf{w}_-\mathbf{H}_+]}{c}$. If this factor is applied to $\mathbf{E}_+$, however, the theory of relativity requires that the same factor shall be applied to the term $\frac{[\mathbf{w}_-\mathbf{H}_+]}{c}$ in order to preserve the necessary properties which the force must have in its relation to the invariance of the equation of motion of an electron under the Lorentzian transformation. Thus, bearing in mind that the classical expression for the force on a negative electron resulting from the field $\mathbf{E}_-$, $\mathbf{H}_-$ remains unchanged, we have, for the whole force on the negative electron

$$\mathbf{F}_- = e\left\{\left(\mathbf{E}_- + \frac{[\mathbf{w}_-\mathbf{H}_-]}{c}\right) + (1+\alpha)\left(\mathbf{E}_+ + \frac{[\mathbf{w}_-\mathbf{H}_+]}{c}\right)\right\} \tag{20}$$

and by analogous arguments the force on a positive electron is

$$\mathbf{F}_+ = e\left\{\left(\mathbf{E}_+ + \frac{[\mathbf{w}_+\mathbf{H}_+]}{c}\right) + (1-\beta)\left(\mathbf{E}_- + \frac{[\mathbf{w}_+\mathbf{H}_-]}{c}\right)\right\} \tag{21}$$

Now, an observer who thinks in terms of the classical theory will measure the magnetic field as the quantity $\mathbf{H}$ which makes $\frac{[\mathbf{w}_-\mathbf{H}]}{c}$ the portion of the force on the electron due to its motion for any direction of that motion. It is thus evident from (20) that

$$\begin{aligned} \mathbf{H} &= (1+\alpha)\mathbf{H}_+ + \mathbf{H}_- \\ &= \alpha\mathbf{H}_+ + (\mathbf{H}_+ + \mathbf{H}_-) \end{aligned} \tag{22}$$

Now the term $\alpha\mathbf{H}_+$ in this expression represents the apparent magnetic field which would be produced by the rotation of a

neutral earth, for which $\mathbf{H}_+ + \mathbf{H}_-$ would be zero. However, because of the charge density ρ which comes into existence on account of the modification of the forces between statical charges, $\mathbf{H}_+ + \mathbf{H}_-$ is not zero. It is in fact equal to the magnetic field due to the rotation of the distribution of density ρ; and,

$$\frac{\mathbf{H}_+ + \mathbf{H}_-}{\mathbf{H}_+} = \frac{\rho}{\rho_+}$$

so that, using (19)

$$\mathbf{H}_+ + \mathbf{H}_- = -\alpha \mathbf{H}_+$$

Thus, from (22), $\mathbf{H} = 0$.

SLOANE LABORATORY,
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The Permanent Polarization of Solid Dielectrics. S. MIKOLA. (*Zeit. f. Physik.*, **32**, No. 6.)—Plates of glass placed for one or two minutes in an electrical field of 8000 volts per cm. were found to have become polarized in such a way that the side of the glass toward the positively-charged anode was negatively charged while the side facing the cathode was positively charged. The name "internal polarization" is bestowed on this type. Varieties of glass differ greatly in their ability to assume this kind of polarization. The Hungarian investigator discovered that there are two kinds of paraffin, one of which can be thus polarized, while the other cannot be. There are three ways of preparing paraffin that takes internal polarization. (*a*) By melting the solid and by heating the resulting liquid far above the melting-point, up to 200° C. Slabs cast from this have the property. (*b*) A slab of ordinary paraffin, subjected to X-rays, shows the property after the removal of the polarization due to the direct action of the rays. (*c*) Finally the mere elevation of the temperature of solid paraffin above 26° seems to be effective. All the media thus capable of polarization have electrical conductivities from 100 to 10,000 times as large as those which cannot assume this state. "The electrical field separates the free ions located in the material and makes them movable. In consequence the positive ions move in the direction of the field and the negative ones in the opposite direction through the material as is the case in electrolytes or in ionized gases. Thus there forms in the neighborhood of the anode an excess of negative ions and near the cathode a corresponding excess of positive ones. Since the mobility of ions in the solids employed must be taken as small, we can understand why the distribution attained remains after the disappearance of the external field."

There follows a discussion of the mechanism of the production of another type of polarization in which the distribution of charges is the opposite to that just described. G. F. S.

HIGH-POWER METALLOGRAPHY—SOME RECENT DEVELOPMENTS IN PHOTOMICROGRAPHY AND METALLURGICAL RESEARCH.*

BY

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INTRODUCTION.

THE usual conception of high-power metallography seems to be great enlargement, indistinct definition and lack of resolution. Such results, generally, have been classed under the heading "empty magnification" because they have failed to show more detail than has been shown at lower magnifications and with objectives of less resolving ability. Oftentimes the pictures would be unintelligible taken by themselves, but the reason they are recognized at all is because the same structures have been seen and identified by low- or medium-power methods. Such high-power results are like an elastic band which has been stretched unduly. As the band is stretched it becomes more and more attenuated and finally snaps. If the optical image is stretched by enlargement the details of the image become less and less distinct and finally the image breaks down altogether, so that the detail and the background blend together into a hazy outline of what formerly was a sharp image.

"Empty magnification" is illustrated in Fig. 1, which shows the normalized structure of a low carbon steel at high magnification. The photomicrograph was taken during the early development work in high-power metallography. It is obvious that a point in the object has become a halo in the image or, expressed differently, the "circle of confusion" is so large that the image is indistinct. The picture is exceedingly "flat," due to diffusion of the light and to overlapping of the halos.

High-power metallography as here presented consists of so preparing metallurgical specimens that crisp brilliant images may be obtained and photographed at high powers and of achieving approximately the potential resolving possibilities of splendid objectives.

* Presented at a meeting held Thursday, December 4, 1924.

By improvements in the method of preparing metallurgical specimens and in the technique of manipulating the apparatus, "empty magnification" is no longer synonymous with high-power photomicrography.

It is the object of this contribution to show the application of this new tool for metallurgical research to the study of metal structures which heretofore have not been resolved and the nature of which has led to much speculation and to wide differences of opinion. A clear understanding of the current conceptions of

FIG. 1.

Empty magnification. Magnification without resolution.

magnification and resolution is essential and a knowledge of the limitations which were regarded for many years as restricting the employment of high powers will prove of value in the interpretation of the results obtained. For this reason a brief discussion follows which not only shows the method of approach in the present development, but indicates the path along which we may work to secure a higher order of resolution.

An objective of given numerical aperture when used with light of given wave-length has some fixed limit of resolution. By resolution is meant that property of a lens system which enables it to distinguish or "resolve" as separate and distinct units fine structural details spaced very close together.

The best high-power objectives of 1.40 numerical aperture are capable, theoretically, of resolving about 140,000 lines per inch

when used with a filter which transmits blue or blue-violet light or of wave-lengths 4000 to 5000 Ångström units. Even the most superficial examination of the work of metallographers will convince one that this theoretical limit has not been approached even remotely. Until it is attained the microscope cannot be

FIG. 2.

Transformation from austenite and martensite at one end of an 0.5 per cent. plain carbon steel specimen to pearlite at the other end. Specimen about 1" x ⅜". Magnification, 5½ X.

regarded as an instrument which has yielded its full store of knowledge in the field of metallography.

The ability of an objective to resolve detail is dependent theoretically upon the numerical aperture of the objective and the wave-length of light used.

The relation is expressed numerically by the equation

$$N = \frac{2\,NA}{\lambda}$$

and shows that if the numerical aperture, NA, of the objective is increased or the wave-length, λ, of the light decreased the number of lines, N, capable of being resolved will be increased.

At present the practical limit for numerical aperture of objectives of the apochromatic series is 1.40, although objectives of higher aperture are now an experimental possibility. The wave-length of light used can be confined to the region of the visible spectrum between 4000 and 5000 Ångström units and

FIG. 3.

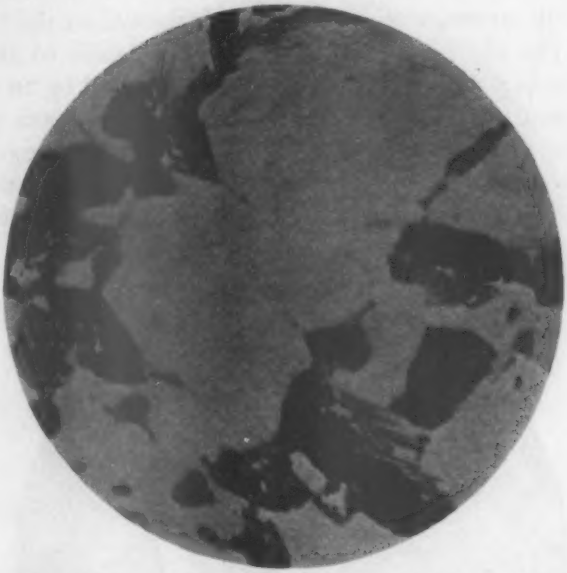
Matrix of austenite and martensite with troostite developing along crystallographic planes. White areas at centre of troostite are ferrite clearing from the troostite. Picric acid etch. Magnification, 3230 X.

still permit short exposures. Thus practical limits are fixed for those who work within the range of the visual spectrum.

It is quite evident that resolution and magnification must bear a relationship. An objective has certain potential resolving ability which may or may not be fully utilized in practice. The ability to resolve detail is an inherent characteristic of the lens, and it is the same at low magnification as at high. The magnification does not add resolution—but it does separate the detail.

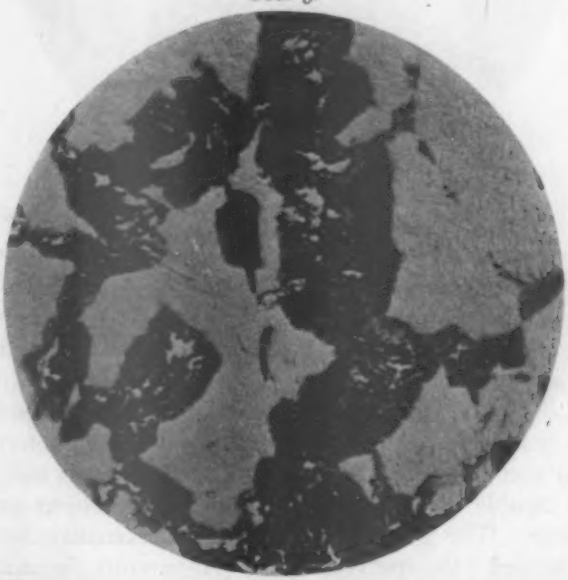
The objective produces the image, the eye-piece and the bellows extension add magnification. Before the image can be photo-

FIG. 4.



Troostite has increased with more free ferrite cleared. The troostite partially surrounds large areas of austenite-martensite. Picric acid etch. Magnification, 3230 X.

FIG. 5.



Troostite still increasing—granular in appearance. More free ferrite cleared from the troostite. Picric acid etch. Magnification, 3230 X.

graphed it must be focussed, and before it can be focussed the detail of the structure must be seen with the eye on the focussing screen. The ability of the eye to perceive details of the image thus becomes a factor. The relation is illustrated by an analogy. It is as easy to count dimes as dollars when the coins are on a table before one. At some distance the dollars are more easily seen than the dimes and we need magnification to see the dimes easily. New coins are like well-prepared specimens, the markings

FIG. 6.

Troostite is now decreasing. Large areas of free ferrite. Picric acid etch. Magnification, 3230 X.

are sharp and distinct and stand out brilliantly, *i.e.*, the details lend themselves readily to sharp focussing. Old coins with worn and rounded markings are like poorly prepared specimens, the detail does not stand out well, and, if much enlarged, blends together or into the background.

Heretofore the practical limit to which magnification could be extended has been considered as about 1500 diameters. This conclusion seems to have been reached on the basis that no lens system is capable of reproducing a point in the object as a point in the image. The point becomes a disc or circular area which has been termed "the spurious disc." Apparently the early inves-

FIG. 7.

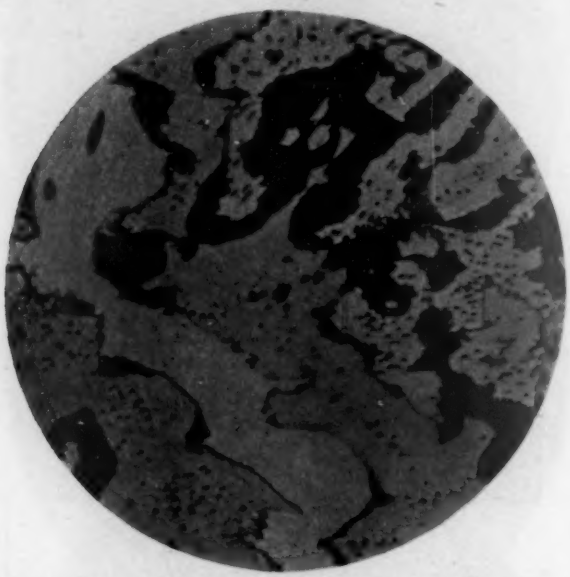
Troostite is fast disappearing, leaving large areas of free ferrite. The residual troostite is granular appearing. Picric acid etch. Magnification, 3230 X.

FIG. 8.

Residual troostite appears slightly striated. Note small black dots in austenite-martensite matrix. This marks the commencement of the precipitation or appearance of ferrite in the austenite and martensite. Picric acid etch. Magnification, 3230 X.

tigators found that when the diameter of this spurious disc exceeds 1/100 inch the image became indistinct and so the diameter of the spurious disc was evaluated in terms of magnification, wave-length of light and numerical aperture. The result of this formula is summarized roughly as 1000 times the numerical aperture of the objective used. Thus when an objective of

FIG. 9.



Large number of ferrite particles have appeared in austenite-martensite areas. Residual troostite has distinctly striated edges. Picric acid etch. Magnification, 3230 X.

1.40 N.A. is used, the limiting useful magnification with this formula would be about 1400 diameters.

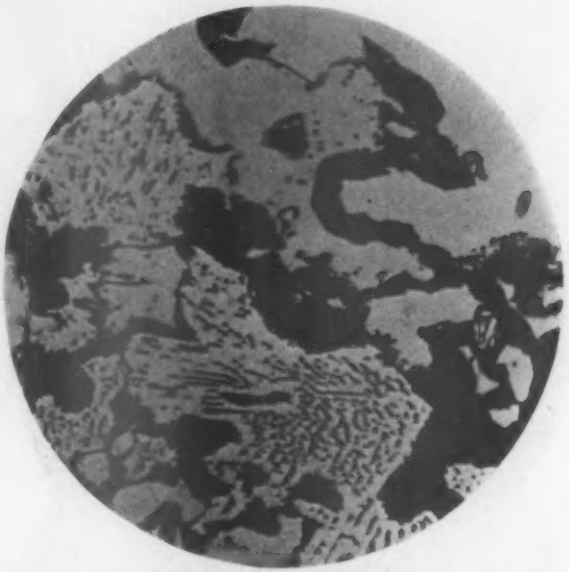
If high magnifications [1] are to be used, the specimen must be prepared with great care, so as to bring out with brilliancy and contrast the particular elements of structure which it is desired to photograph. Starting with a very flat specimen which has been highly polished (so that no scratches or imperfections are visible at the highest powers) the surface is delicately etched and the structure examined from time to time until the required degree of contrast has been developed in the particular constituent

[1] "High-power Photomicrography of Metallurgical Specimens," *Trans. Am. Soc. for Steel Treating*, Dec., 1923. "Photomicrography and Technical Microscopy," *Bell System Tech. Jour.*, Jan., 1924.

which it is desired to study—all else being neglected. As the magnification is increased the area of the field of vision on the specimen is decreased, so by working at high powers and preparing the work at high powers we may deal with smaller and smaller elements comprising the structure of the specimen.

The useful limit of magnification is not the one just expressed because crisp brilliant images have been obtained at high powers. Moreover, resolution has improved as the magnification has been

FIG. 10.



Ferrite dots now elongated. Residual troostite more fully striated along edges. Picric acid etch. Magnification, 3230 X.

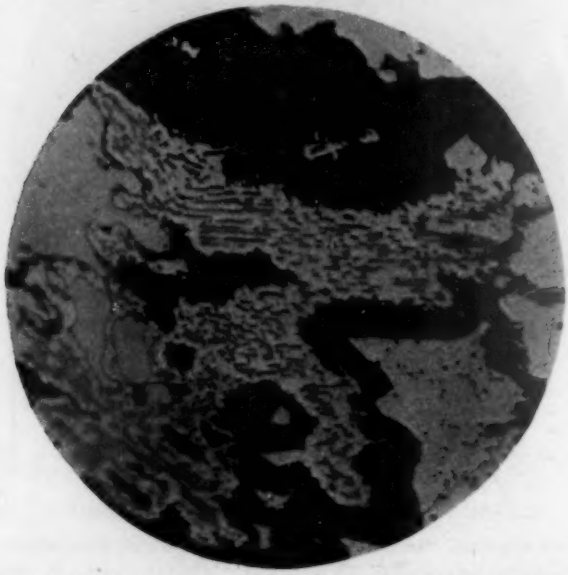
increased. The limit of useful magnification is reached when a further increase shows a falling off in resolution and a decrease in brilliancy and crispness of the image. It may be said—and assuredly so—that the best objectives are much better than our ability to use them to advantage. Careful measurements indicate that the theoretical limit of resolution has been achieved approximately with the apochromatic objectives of 1.40 N.A. Whether a higher order of resolution can be obtained with these objectives remains to be seen. Further improvements in resolution will be obtained by higher aperture objectives or by decreasing the wave-

length of the light used. Both methods of approach are now open. Objectives of 1.65 N.A. have been produced for metallurgical work and are now undergoing experimental investigation. Likewise the possibilities of ultra-violet light are being studied.

SOME APPLICATIONS OF HIGH-POWER METALLOGRAPHY. THE PROCESS OF DECOMPOSITION OF AUSTENITE TO PEARLITE IN A 0.5 PER CENT. PLAIN CARBON STEEL.

Five constituents of steel now are recognized generally by metallurgists and to these constituents have been assigned the

FIG. 11.

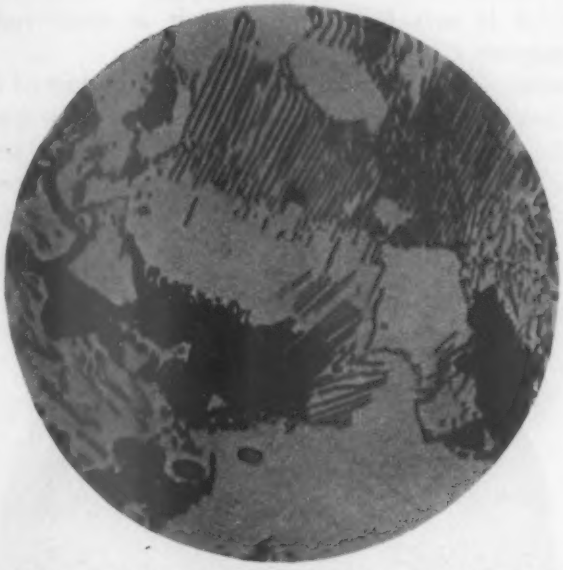


Austenite-martensite areas now nearly converted to lamellar pearlite. Residual troostite is stratifying. Picric acid etch. Magnification, 3230 X.

names: Austenite, martensite, troostite, sorbite and pearlite, in the order of transformation from a higher to a lower order. While agreement prevails as to the existence of five distinctly different structural forms in which steel may be retained, no measure of agreement prevails as to the exact nature of some of these constituents or as to the processes by which the transformations from one to the other are accomplished.

Austenite is regarded generally as a solid solution of iron carbide or carbon in gamma iron and is the condition of steel

FIG. 12.



Well-defined pearlite. Residual troostite nearly stratified. Picric acid etch. Magnification, 3230 X.

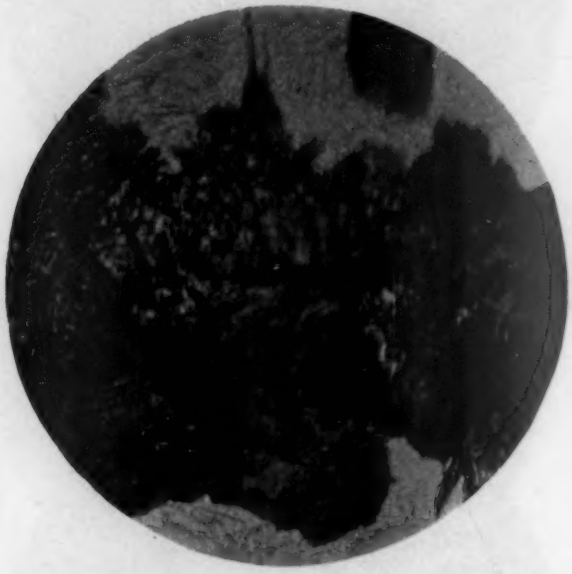
FIG. 13.

Final stage lamellar pearlite. Picric acid etch. Magnification, 3230 X.

which is stable above the critical range. Austenite is non-magnetic; it is soft but tough, and it is quite resistant to etching reagents.

Martensite is considered a decomposition product of austenite. It is the hardest constituent or state of steel and is described as an acicular or needle-like crystal. Almost every conceivable hypothesis has been advanced to explain its nature. Recent work [2] in the field of high-power metallography has shown that marten-

FIG. 14.



An attempt to resolve border-type troöstite. It appears to be a granular flocculent mass which forms small white areas—the free ferrite. Picric acid etch. Magnification, 3230 X.

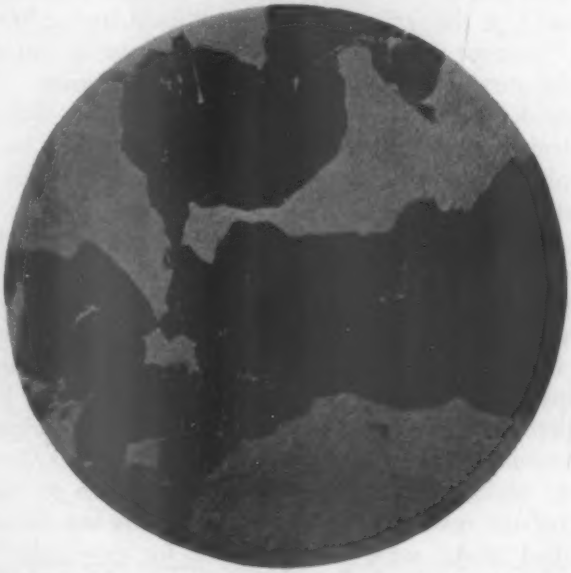
site is a decomposition along the crystallographic planes of austenite and that it responds to two entirely dissimilar etching reagents; one which selects ferrite but does not attack iron carbide, and the other which stains iron carbide but does not affect ferrite. Austenite responds feebly, if at all, to these two etching reagents under the same conditions of application. From this evidence we may conclude reasonably that martensite is an aggregate of iron, probably in the alpha state, and of iron carbide.

[2] "The Micro-structure of Austenite and Martensite," *Trans. Am. Soc. for Steel Treating*, Dec., 1924.

FIG. 15.

Flocculent border-type troostite. Picric acid etch. Magnification, 3230 X.

FIG. 16.



Flocculent border-type troostite. Picric acid etch. Magnification, 3230 X.

Moreover, the high-power microscope shows conclusively that under suitable conditions of etching, martensitic needles display mother-of-pearl colors. This suggested that the structure was laminated, and further investigation at high powers seems to confirm very clearly that martensite is composed of fine lamellæ, probably the continuation of the crystallographic planes of the austenite. It also seems true that the component crystals, elements or particles composing martensite are of a size just bordering on the present range of microscopic resolution. Martensitic needles do not respond to a test for crystallinity, *i.e.*, they fail to show orientation phenomena when revolved about the optical axis of the microscope.

Under certain conditions of heat treatment not as yet fully understood, martensite appears to form or precipitate cubic crystals of ferrite.

It seems to be inferred generally that a grain of austenite is converted to a grain of martensite and this to a grain of troostite. The high-power microscope tells us that there are two distinctly different types of troostite. One is styled "nodular troostite" because of the nodular or globular shapes in which it forms. This is a condition which has been known for some time. The second type the writer has termed "flocculent or border-type troostite" because of its appearance and because it forms usually as a border surrounding an austenite-martensite area.

The evidence points very strongly to the fact that in plain carbon steels appreciable quantities of austenite may be retained at atmospheric conditions even in medium carbon steels, such as those containing not more than 0.5 per cent. carbon. It also may be said that in no case has a specimen been found which consists entirely of martensite. Usually the structures at high powers are found to be mixtures of austenite and martensite or of austenite, martensite and lower orders of decomposition. Nodular troostite is not necessarily a decomposition product of martensite. It develops as well from austenite as from martensite. The high-power microscope shows that in a specimen of a plain iron-carbon alloy, austenite is found which in some places has decomposed directly to nodular troostite and in other places to martensite. The martensitic needles develop troostitic areas but often seem to be absorbed along with the austenite by developing nodules of troostite.

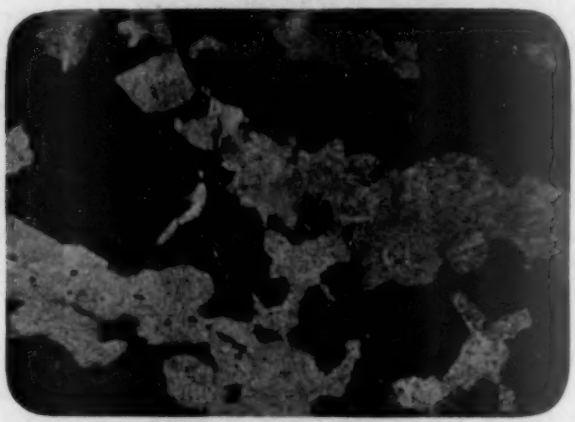
FIG. 17.

Flocculent border-type troostite when freshly formed does not show orientation phenomena when revolved about the optical axis of the microscope. Picric acid etch. Magnification, 3230 X.

In steels of carbon content, perhaps of 0.5 per cent. or more, the entire mass of the metal may be passed through the nodular troostitic stage by suitable methods of heat treatment or it may be heat treated in such a way as to prevent almost entirely the formation of this particular constituent.

In the same series of experiments evidence has been obtained showing that the austenite and martensite matrix may contain tiny cubic crystals of ferrite which seem to form along crystallo-

FIG. 18.



When the specimen shown in Fig. 2 is etched with boiling sodium picrate the austenite is unstained; the martensite is deeply stained; the troostite is very faintly stained and the ferrite at the centre of the troostite is unstained. This field is at the hard side of the transformation. Magnification, 3230 X.

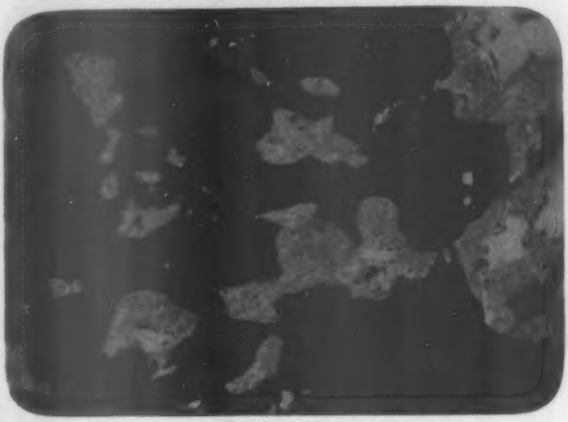
graphic planes and by union and growth develop to form the ferrite lamellæ of the pearlite. It also will be seen from what follows that the carbide lamellæ of pearlite may be formed in the same manner.

If a specimen of rolled and normalized steel is heated to a high temperature at one end while the other end is maintained at room temperature, and then if the whole rod is quenched in an ice and brine solution, it is evident that all transition stages will be found in the specimen. At the heated end will be austenite and martensite, and at the cool end will be laminated pearlite.

By suitable manipulation an abrupt transformation can be secured as shown in Fig. 2, which is a longitudinal section of a 0.5 per cent. commercial plain carbon steel specimen heat treated as described. The specimen is about one inch in length and

3/8 inch in breadth. The dark end is so hard that it was necessary to cut the specimen with a grinding wheel; the other end is soft and ductile and was cut with a hack-saw.

FIG. 19.



Nearer the transformation than Fig. 18. Accumulation of ferrite appears in the troostite. Sodium picrate etch. Magnification, 3230 X.

A steel of this carbon content has a structural composition in the normalized condition of 40 per cent. free ferrite and 60

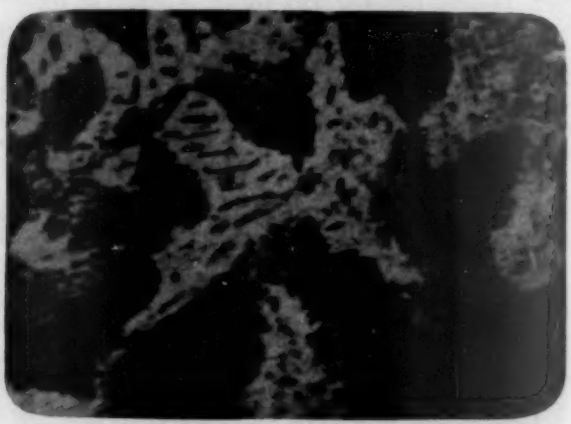
FIG. 20.

Large accumulations of ferrite; the austenite-martensite areas are contracted. Sodium picrate etch. Magnification, 3230 X.

per cent. pearlite, so that between the hard end and the soft end there must have been liberated large quantities of ferrite.

If after preparation for high-power examination this specimen could have been enlarged in its entirety 3230 times, it would have

FIG. 21.



At higher power the borders surrounding the austenite-martensite areas are seen to be iron and iron carbide in the process of stratification. Sodium picrate etch. Magnification, 6000 X.

become a highly polished steel surface about 300 feet long and 100 feet wide, on which the various transformation products

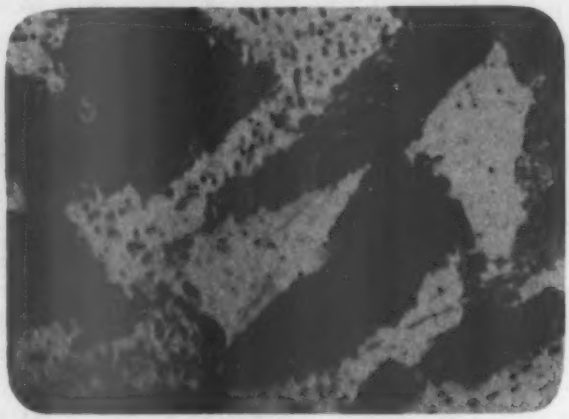
FIG. 22.

Stratification well advanced. Austenite-martensite areas smaller. Residual troostite stratifying. Sodium picrate etch. Magnification, 3230 X.

would appear etched. If one could walk along this steel highway from the hard end to the soft end, he would see the exact manner

in which the austenite and martensite decompose to form pearlite under the conditions of the experiment, and by suitable means he

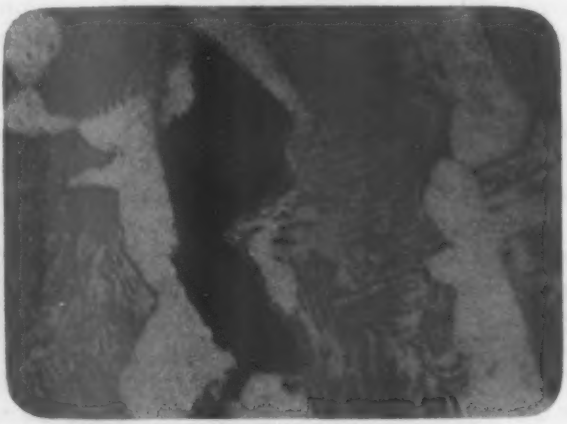
FIG. 23.



Higher power shows well-defined stratification in gray borders of Fig. 22. Magnification, 5600 X.

could detect the differences in hardness as he proceeded. Thus, in a specimen of this sort is written the story of the hardening of

FIG. 24.



Nearly lamellar pearlite except for small area of austenite-martensite. Magnification, 3300 X.

steel and of the transformations for the specified conditions of heat treatment.

Unfortunately, a reagent is not known, to the writer at least, which will etch equally well at the same time all of the transformation products of steel and to the precise degree required for high-power work. When all constituents exist in the same specimen a compromise must be made and as a result some of the constituents will be slightly over-etched and others slightly under-etched. Thus, to a certain extent, brilliancy and contrast are sacrificed.

For the first series of pictures, the specimen was carefully prepared longitudinally and then etched with a 5 per cent. alcoholic picric acid solution. This etching reagent attacks ferrite, but does not stain or etch iron carbide. The specimen was mounted on the mechanical stage of the microscope and passed before the objective from the hard to the soft end. At intervals photographs were taken to show by rather gradual stages the complete sequence of events. The magnification is 3230 X.

At the hard end (Fig. 3), a matrix consisting of austenite and martensite is found. The austenite is clear white and the acicular needles of martensite are etched light brown. Along some of the cleavage planes indicated by the martensitic needles, dark streaks of troostite have developed, and at the centres of some of the troostitic areas a white constituent appears, which is identified as ferrite. In order to bring out the acicular structure of the martensite, it was necessary to take the following pictures first and then re-etch slightly deeper to bring out the martensite for Fig. 3.

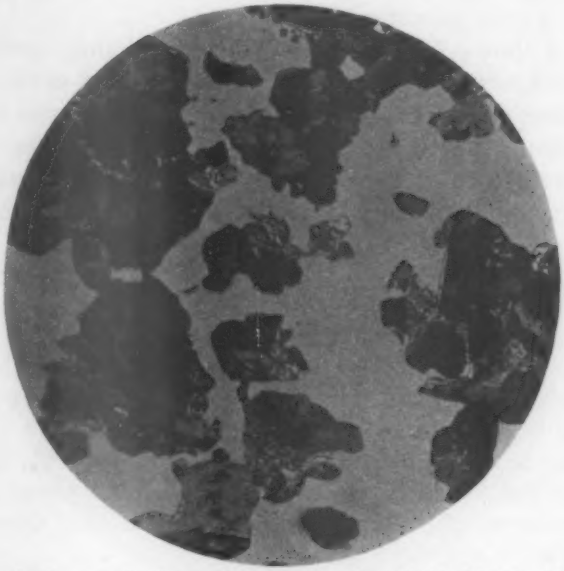
As the specimen is moved along the troostite increases (Fig. 4) and partially surrounds large areas of the austenite and martensite matrix. At the centre of the troostitic areas the free ferrite is increasing. That is, the troostite has increased in volume and some free ferrite has cleared from the troostite.

In Fig. 5, which marks a further advance, the troostite is still increasing but now appears rather mottled or granular. The free ferrite has increased in volume.

If the entire mass of the metal is to pass through the troostitic stage, then there should be a rapid increase in the volume of troostite, but in Fig. 6, which is a slightly advanced position from that of the preceding figure, the troostite is found to be decreasing, leaving large areas of free ferrite.

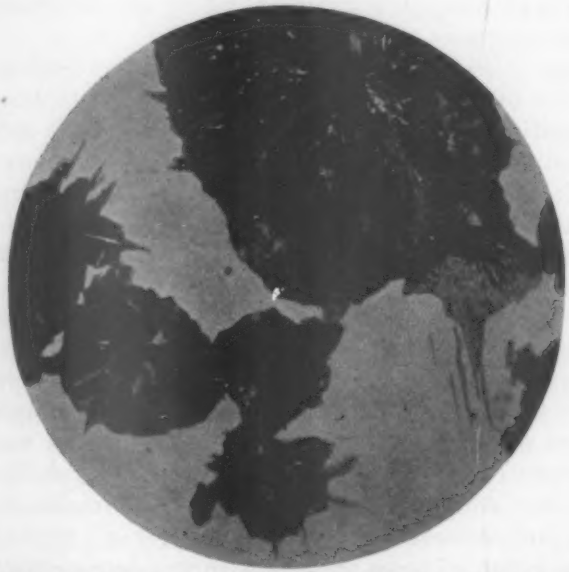
Fig. 7 is still further advanced and now the troostite is fast

FIG. 25.



Nodular troostite in a matrix of austenite and martensite. Picric acid etch. Magnification, 1300 X.

FIG. 26.



Nodular troostite development arrested in some directions by interference of growing nodules. Picric acid etch. Magnification, 2220 X.

disappearing with an increase in the free ferrite. The residual troostite is quite granular in appearance.

Fig. 8 shows the residual troostite as slightly striated, and close observation shows small black dots appearing in the austenite and martensite areas. This marks the commencement of a new phenomenon, namely, the appearance of ferrite in the austenite and martensite. If this specimen were carefully prepared to bring out clearly these small dots, they would be found to be tiny cubic pits.

As the specimen is moved forward, the dots increase in number and in Fig. 9 a large number is shown. The residual troostite now has distinctly striated edges.

A further advance of the specimen (Fig. 10) shows the dots becoming elongated and the residual troostite more fully stratified along the edges.

In the next position on the specimen (Fig. 11), it will be seen that the former austenite and martensite areas are now nearly converted to lamellar pearlite and the residual troostite is in the process of stratification.

Fig. 12 marks a further advance in the stratification of the austenite and martensite areas and of the residual troostite which now is almost completely stratified, taking on the orientation of the adjoining grains.

In Fig. 13 is shown the final stage of lamellar pearlite.

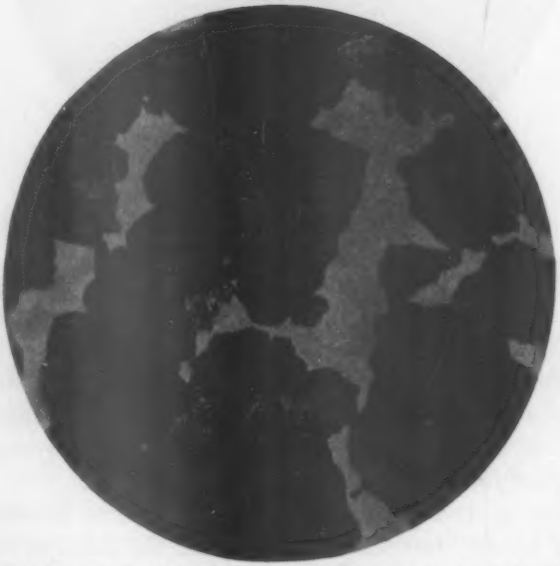
In order to develop the structure of the freshly formed troostite, the specimen was reprepared and very carefully etched. By concentrating attention on the troostite and making every effort to resolve the structure, it is found to be a flocculent, granular mass containing many small white areas. This is shown in Fig. 14. Other views of the structure of flocculent border-type troostite are shown in Figs. 15 and 16.

This form of troostite appears to be ferrite in a disorganized state of crystallinity, but it carries some carbon or iron carbide. When freshly formed, it fails to respond to a test for crystallinity, as shown in Fig. 17; and probably it is the closest approach to amorphous metal within the range of the high-power microscope. The particles composing flocculent troostite are probably crystalline, but they are not within present range of resolution. However, the particles must soon orient themselves in a regular fashion under the action of some prevailing forces, because the troostite

FIG. 27.

A

B



Resolution by high-power methods. The same specimen and the same objective as Fig. 25. Magnification, 3230 X.

soon develops areas of uniformly oriented ferrite. When the composition of the flocculent troostitic mass has been reduced to eutectoid proportions by clearing of the excess ferrite, the residual mass consisting of a matrix of austenite and martensite stratifies to form lamellar pearlite.

The conditions existing when troostite of this type is freshly formed may be imagined by assuming a number of tiny cubical

FIG. 28.

Incipient stratification taking place in a radial troostitic grain. Picric acid etch. Magnification, 6000 X.

blocks, built up regularly on a piece of gauze or mesh material laid upon a table. If the corners of the gauze are folded over and grasped to form a bag, the whole may be shaken vigorously. Because the blocks are confined loosely, they orient themselves differently, and a heterogeneous or " amorphous " arrangement of flocculent troostite is pictured—the elements are crystalline but their regularity of orientation has been disturbed.

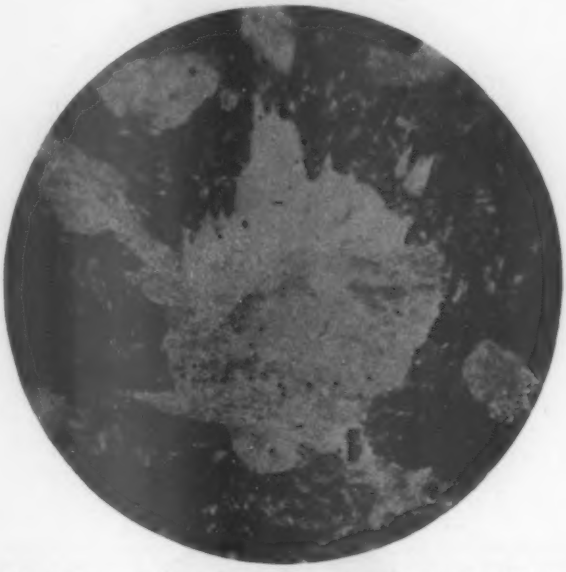
In order to trace the evolution of the carbide lamellæ of the pearlite, it is only necessary to reprepare the specimen and etch with boiling sodium picrate in place of the picric acid solution pre-

viously used. Sodium picrate stains the carbide dark, as already noted, but has no effect on the ferrite.

Fig. 18 is near the hardened side of the transformation in the specimen. The martensite is stained dark; the troostite a very light gray and the ferrite, just appearing in the centres of the troostitic regions, is white.

In Fig. 19, which is a stage further advanced in the transformation, the ferrite areas are now narrow bands, and in Fig. 20,

FIG. 29.



Nodular troostite stains very faintly with sodium picrate which selects carbides. Magnification, 3230 X.

which is still further advanced, large accumulations of ferrite are seen in the troostitic areas.

Proceeding further, the martensitic areas seem considerably contracted and large areas of ferrite are present which are surrounded by striated or granular appearing borders, as shown in Fig. 21. If these borders are examined under still higher powers, they are seen to consist of a light and a dark constituent in the early states of stratification.

In Fig. 22 the process is still further advanced. The striated borders are plainly seen and the martensitic areas are stratifying.

FIG. 30.

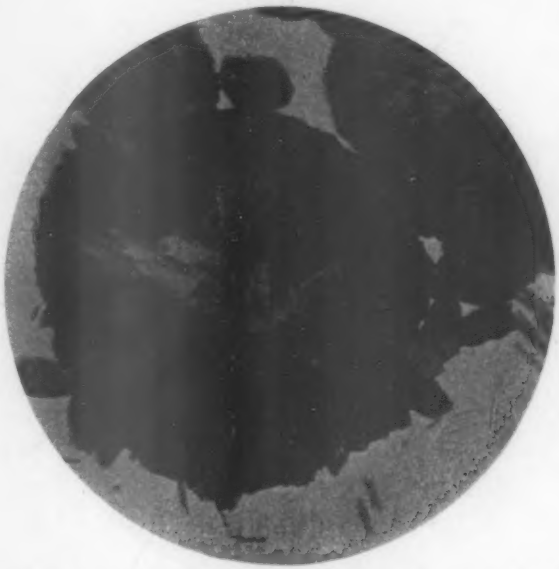
When nodular troostite is revolved about the optical axis of the microscope it displays orientation phenomena. Picric acid etch. Magnification, 3230 X.

Higher powers again show very well-defined stratification, as is apparent from Fig. 23.

In Fig. 24, the metal has completely stratified except for small martensitic areas as noted. These small areas gradually disappear by the process of stratification and the final stage of lamellar pearlite is reached.

The transformations taking place in the 0.5 per cent. plain

FIG. 31.



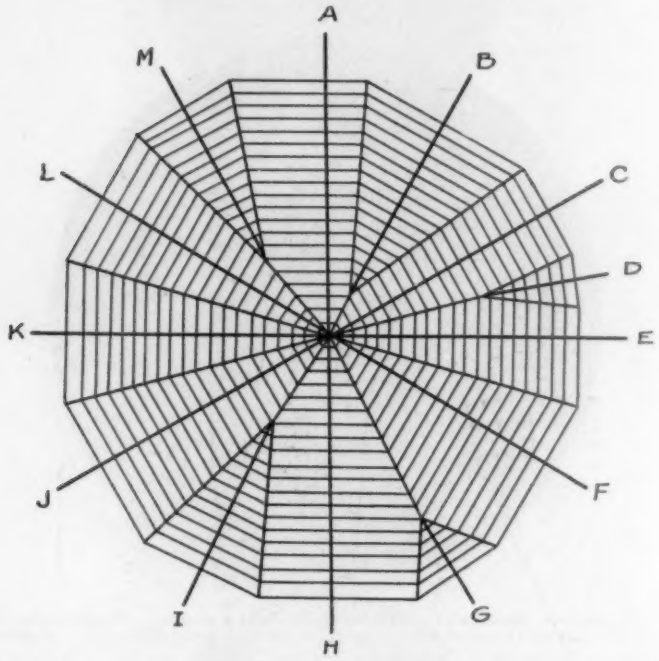
Nodular troostite develops as a globular mass about a nucleus. Radial grains develop. When nodular troostite forms regranulation must occur. Picric acid etch. Magnification, 3230 X.

carbon steel, under the conditions defined for the experiment, may be briefly summarized as follows:

At high powers the hardened end is seen to consist of a network of martensitic needles in austenite. As the field under examination approaches the abrupt transformation, dark streaks of troostite appear along some of the martensitic needles. Small white areas, ferrite, soon appear in the centre of the troostitic areas. As the troostite increases, it appears to form a border, enclosing relatively large areas of austenite and martensite. The troostite continues to increase until it reaches a maximum and then it decreases, leaving large areas of austenite and martensite

untransformed. As the troostite increases, the central areas of ferrite increase rapidly. When no more troostite is formed the ferrite areas continue to increase at the expense of the troostite, thus causing the troostite to decrease and finally to disappear, except for a small border surrounding large areas of ferrite. Evidently this residual troostite, as it might be called, is then of

FIG. 32.



Section through a troostitic nodule depicting crystalline growth from nuclei along axes of crystallization, A, B, C, etc.

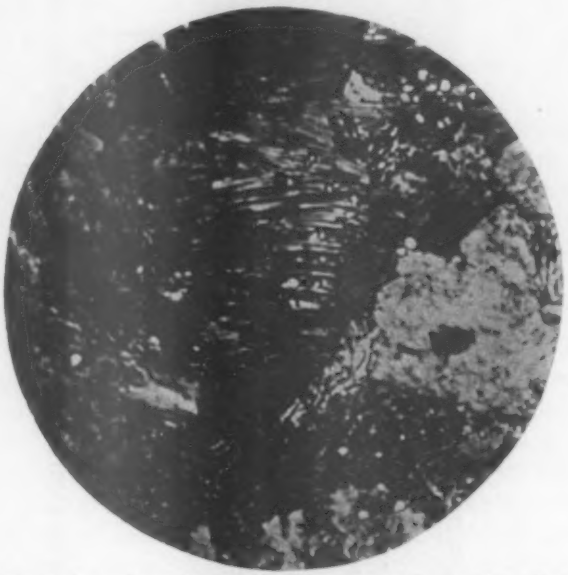
eutectoid proportions as it stratifies, taking on the orientation of the adjoining grains. About the time the troostite has nearly cleared to ferrite, the areas of austenite-martensite commence to develop tiny cubic pits. These increase in number along the cleavage planes of the austenite. Soon the cubic pits are found to have united so as to form long bands of ferrite, and thus it will be seen that stratification to laminated pearlite takes place in the former austenite and martensite areas without these areas passing through troostite.

If the specimen is repolished and etched with boiling sodium

picrate, the carbides are deeply stained; the troostitic areas are only faintly stained; the martensite is darkly stained, and the ferrite unstained. As the process advances, carbide particles appear in the austenite and martensite and the residual troostite borders are seen to form lamellæ of carbide.

When a specimen of 0.5 per cent. plain carbon steel is heat treated in the manner described, the troostite formed appears to be a rough measure of the excess ferrite present. The troostite

FIG. 33.



Expulsion of free ferrite and stratification in a grain of nodular troostite. Picric acid etch. Magnification, 3500 X.

is a flocculent mass analogous to a precipitate. It fails to show crystalline orientation under high powers, but the particles soon arrange themselves in a regularly oriented fashion and become the free ferrite. Using the highest resolving power possible, freshly formed flocculent troostite appears to be a mottled substance containing many small white areas—the cleared or regularly oriented ferrite. When the metal has been reduced to eutectoid proportions by the expulsion of the free ferrite, the remainder, consisting of a matrix of austenite and martensite, stratifies and forms laminated pearlite without first passing through the troostitic stage.

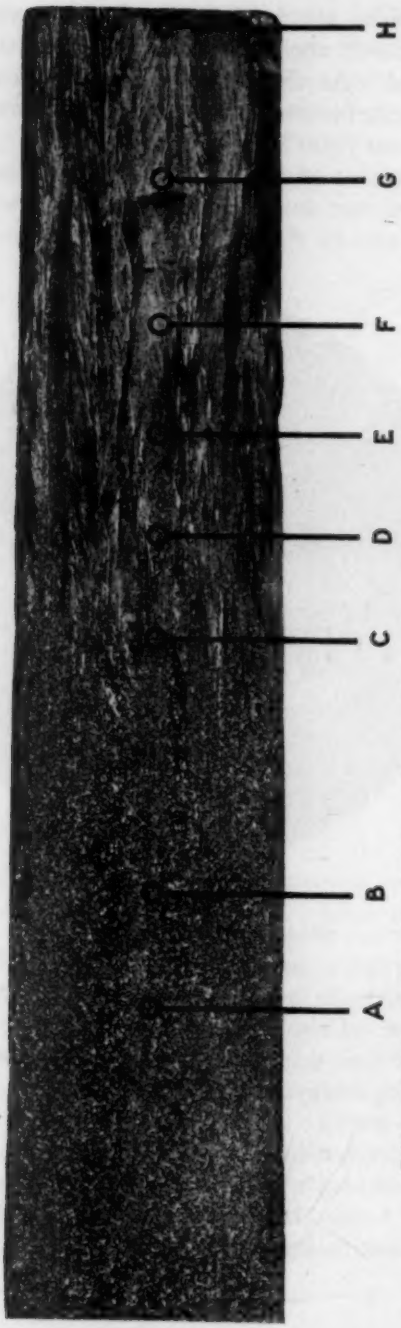


FIG. 34.

Cold work and regranulation in a nickel-iron alloy. Low-power picture taken at 23 X and high-power pictures at 2560 X.

NODULAR TROOSTITE.

Troostite has been regarded as an uncoagulated mixture of transition products. The high-power microscope supplies some convincing evidence that nodular troostite is a definite and an orderly step in the transformation.

Nodular troostite appears to result when the specimen is quenched under approximately uniform conditions. In the experiment just described, flocculent border-type troostite was produced in a 0.5 per cent. carbon steel; but if a specimen of this same steel is heated uniformly and quenched, nodular troostite results. As previously stated, it appears that in the latter case the entire mass of the metal will pass through the nodular troostitic stage.

Nodular troostite may develop directly from austenite or it may develop from a matrix of austenite and martensite. Usually it has its origin in a martensitic needle—along the midrib or at the junction of two needles. About this nucleus under ideal conditions of growth a roughly globular mass develops which seems to absorb both austenite and martensite. In the early development stages the martensitic needles appear incompletely absorbed or transformed and often may be seen as dark areas as though in the background of the nodule. These nodules develop from innumerable nuclei throughout the austenite and martensite matrix. Such a condition is illustrated in Fig. 25. The nuclei increase in number and the developing nodules become larger and larger. Irregularities in growth due to interference of nodules occur as the growing particles increase in number and size until finally the whole mass seems to be composed of nodules, some spherical in shape but many deformed due to mutual interference and to irregularities in growth. A selectivity or preference in crystal habit probably prevails for crystallographic planes since spines, branches, and interconnected crystallites may be found occasionally. In reality these are poorly formed nodules, growth in some one or more directions having been arrested (Fig. 26).

It is quite evident that if the entire mass of the metal passes through the nodular troostitic stage, this constituent must contain carbide or carbon in some form.

When one of the globular-shaped crystal masses which has developed under favorable conditions of growth is sectioned in such a way as to divide the mass along a plane passing through

FIG. 34.

A

B

See Fig. 34.

FIG. 34.

C

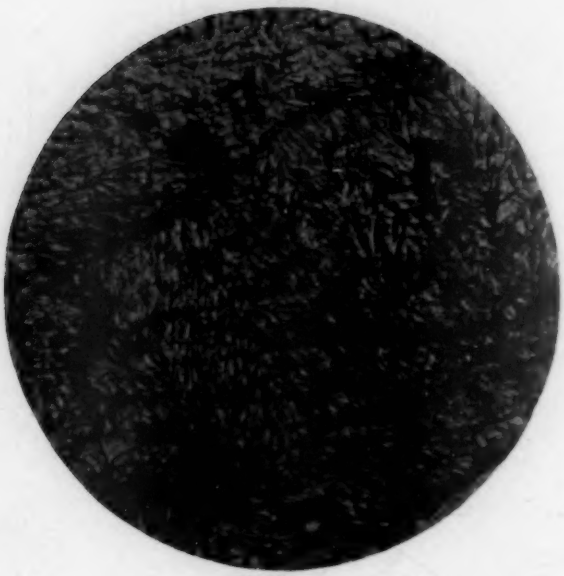
D

See Fig. 34.

FIG. 34.

E

F



See Fig. 34.

FIG. 34.

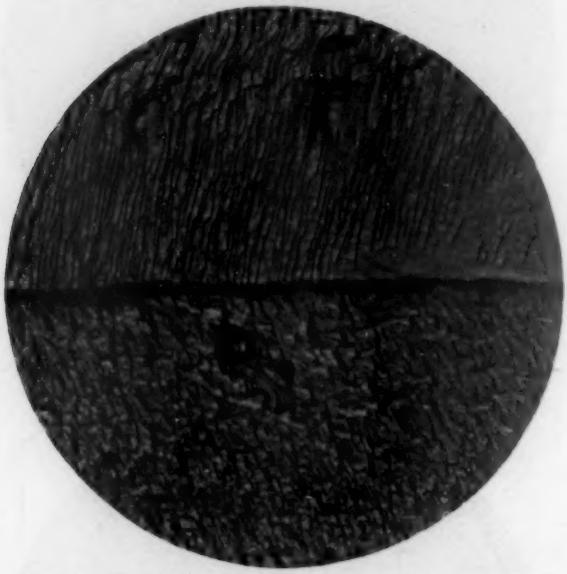
G

H

See Fig. 34.

the centre, the nucleus is found at the centre and fan-shaped grains extending from the centre toward the outside. When freshly formed and under the highest powers of the microscope, these radial grains have all of the appearance of a solid solution. The nodule must contain carbon in some form, as stratification soon takes place. This is illustrated in Figs. 27 and 28. In Fig. 29 is shown a troostitic nodule etched with boiling sodium picrate

FIG. 35.



Grain boundary in a nickel-iron alloy. Magnification, 2560 X.

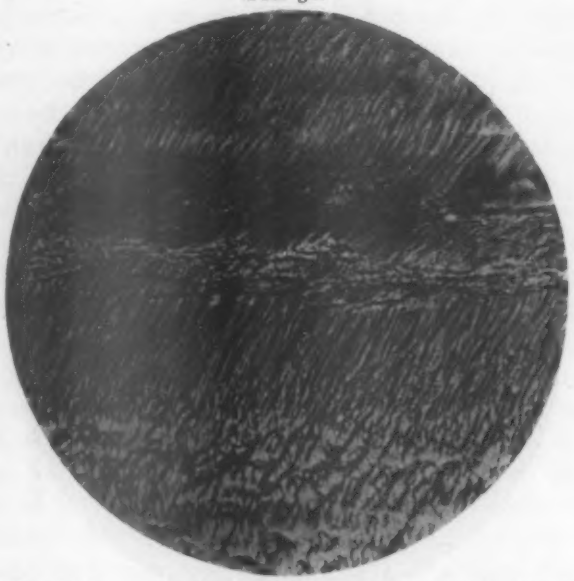
which darkens carbide. By this reagent, the nodule is stained faintly, if at all.

If carbide is present in nodular troostite as an aggregate with iron, the size of the carbide particle must be very small—well beyond the present range of microscopic vision, because nodular troostite, when freshly formed in plain carbon steels, does not etch with sodium picrate. In the case of martensite this etching reagent has been found to darken the needles. If carbon is present in nodular troostite as carbon rather than carbide, evidence is lacking as to whether sodium picrate would select it by staining. If carbide is in solid solution, it appears to be beyond reach by microscopic methods. The most logical state of affairs seems to

be that nodular troostite is either a solid solution of iron carbide in iron or it is a very fine aggregate of iron and iron carbide—the carbide so finely dispersed as to lose its identity under the microscope. If we accept the view that nodular troostite is a solid solution, it would appear that when the nodule first forms the iron must be present in some state capable of holding iron carbide or carbon in solid solution.

After the nodule has formed, the next stage in decomposition

FIG. 36.



Slip bands in a cold-worked nickel-iron alloy. Magnification, 2560 X.

appears to be elimination of the excess constituent, ferrite in the case of hypo-eutectoid steels or cementite in hyper-eutectoid steels, in tiny globular particles. These globules appear to be forced to the grain boundaries. Simultaneously with this expulsion of the excess constituent, stratification sets in and the segmental or radial grains of the troostitic nodule are transformed to grains of pearlite by a separation of ferrite and carbide along definite planes.

If a globular mass develops about a nucleus by uniform growth of cubical crystalline elements, it seems reasonable to expect that changes in orientation probably occur. When nodular troostite is tested for crystallinity, it displays orientation phenomena very

definitely, as shown in Fig. 30. Where changes in orientation take place, grain boundaries must result. Thus it seems that when nodular troostite develops, the metal regranulates without particular reference to the original polyhedral austenitic grain boundaries. That is, a grain of austenite is not converted to a grain of troostite, as appears to be one conception of the transformation, but it develops a number of troostitic nodules, each of which develops a number of little radial grains. On reflection, it would seem impossible to build a globular mass about a nucleus by the process

FIG. 37.

Twinned areas in a nickel-iron alloy. Magnification, 2560 X.

of crystallization and not have well-defined lines at which the orientation changes. In Fig. 31 is shown a section of a well-formed troostitic nodule and Fig. 32 is a diagrammatic representation of how regranulation appears to have taken place. Fig. 33 shows the expulsion of free ferrite in small globular masses and the early stages of stratification.

COLD WORK AND REGRANULATION.

When cold-worked metals are annealed the metal regranulates, the strains due to cold working are relieved and the metal becomes

soft and ductile again. The cycle of events may be shown graphically by means of low- and high-power photomicrography.

A cold-rolled rod of permalloy (78.5 per cent. Ni to 21.5 per cent. Fe) about ⅜ inch in diameter and 10 inches in length was annealed at one end, while the other end was maintained cool. The annealed end, of course, regranulated and the regranulation blended into the cold-worked metal. A section was then taken from the specimen at the place where the cold-worked and the annealed portions blended. This section was prepared longitudinally for metallographic examination and was photographed in its entirety at low magnification. Then a series of high-power pictures was taken from the cold-worked end to the annealed end, the exact location of each high-power picture being determined by measurements and plotted on the low-power photograph (Fig. 34).

At the cold-worked end the high-power picture, Fig. 34 *H*, shows the metal to be very severely strained and distorted. A little further along at position *G*, the structure shows the early stages in the elimination of mechanical strains, but in this position the metal is still badly distorted. In Fig. 34 *F* certain areas in the large grains seem to have become somewhat reoriented but the process was arrested before completion. The next position, Fig. 34 *E*, shows the reorienting process carried more nearly to completion as is evident by the rearrangement of the metal apparently to form the smaller grains. Twinned areas may also be seen clearly. As the field under examination progresses toward the annealed end, recrystallization is seen to take place with the gradual disappearance of the strained and distorted structure due to the deformation of rolling. The progressive stages in the gradual vanishing of mechanical strains due to the effect of annealing are further illustrated in Figs. 34 *D*, *C*, *B* and *A*, in the order named.

In Fig. 35 grain boundaries are seen to be a perfect keying of the crystalline elements of one grain into the crystalline elements of an adjoining grain. Slip bands are distortions along the cleavage planes, as the name implies, but incipient fissures are also seen to be present in Fig. 36. Twinned areas gradually develop by a reorientation process and at high powers are illustrated in Fig. 37.

In the low-power photograph it will be noted that by cold work the large elongated grains produced persist in a sort of phantom outline, even though the metal has regranulated, due to annealing for a long period of time. The phenomenon appears to be due to a certain uniformity or regularity of orientation of the small grains along directional lines inherited from the large cold-worked grains from which the smaller grains formed when the metal was annealed.

Action of Hypochlorites upon Metallic Ruthenium.—JAMES LEWIS HOWE and FREDERICK N. MERCER, of Washington and Lee University (*Jour. Am. Chem. Soc.*, 1925, **47**, 2926–2932), have studied the action of sodium hypochlorite in aqueous solution upon finely divided metallic ruthenium and its compounds. They are completely soluble in this solvent. When an excess of alkali is present, ruthenates are formed. When alkali is not present in excess, some ruthenium tetroxide is produced. If the sample be finely divided, ruthenium can be separated from the other platinum metals except osmium by solution in an alkaline hypochlorite. These investigators have also found that the ruthenium can be completely distilled as its tetroxide, after a solution of potassium ruthenate has been treated with chlorine. No satisfactory method has yet been devised for the quantitative precipitation of ruthenium from the tetroxide in weighable form. J. S. H.

Vehicular Tunnel under the Mersey River. (*Compressed Air Magazine*, Jan., 1926, p. 1516.)—A road tunnel, to connect Liverpool and Birkenhead, England, is to be constructed under the River Mersey at a cost of £5,000,000. Work on the project is to commence at an early date. The point chosen for the passageway is at the narrowest part of the river; and the outlets are so planned—two on the Liverpool side and one on the Birkenhead side—that no congestion in entering or leaving shall result. The tunnel will permit two lines of traffic to move in each direction, and will have a capacity of 2000 vehicles an hour. Gradients will be 1 in 30 for slow-moving or heavy vehicles and 1 in 20 for fast or light traffic.

The tube will be of cast iron; and the space between the tube and the sandstone rock is to be completely grouted with a cement or a lime mixture applied under pressure. This mixture will be forced in a semi-fluid condition through holes in the castings, which will be sealed subsequently with screw plugs. The tunnel is to have an internal diameter of 44 feet, allowing for a roadway 36 feet wide between curbs and a narrow foot-path on each side. The sectional areas not required for traffic are to serve as inlets for fresh air and for exhausting the vitiated atmosphere—thus avoiding the use of air at high velocity for the ventilating of the tunnel. The air will be fed under the roadway and pass up and out through exhausts overhead.

ELECTRICAL DISCHARGES BETWEEN HIGH-RESISTANCE ELECTRODES.*

BY

J. SLEPIAN, Ph.D.

Research Department, The Westinghouse Electric and Manufacturing Company.

IN THE preceding paper [1] it has been shown that the transition from a glow discharge to an arc at atmospheric pressure is not due to the heating of the cathode by the glow, but that the glow changes over into a low-voltage concentrated discharge long before the cathode reaches a high temperature. In particular, a discharge was considered which was started disruptively between cold electrodes. So long as the discharge remained a glow, the temperature rise for the cathode for various metals calculated out to be not more than

$$\begin{aligned} &\text{Copper,} && T = 226\ \sqrt{t} \\ &\text{Brass,} && T = 985\ \sqrt{t} \\ &\text{Iron,} && T = 509\ \sqrt{t} \\ &\text{Platinum,} && T = 1040\ \sqrt{t} \end{aligned} \qquad (1)$$

where t is the time in seconds. Hence the glow discharge would have to last for a matter of seconds before the cathode became hot enough for thermionic emission, or even before it became hot enough for melting. Experimentally, it was found, however, that in less than 10^{-5} seconds, the glow concentrated into a low-voltage discharge, with pitting of the electrodes.

In the preceding paper,[1] the theory was advanced that the transition from glow to arc is caused by heating and thermal ionization of the gas in the cathode dark space. This thermal ionization causes an increase in current density, which in turn causes a further increase in the cathode dark space temperature and so produces an instability whereby the whole current converges into a single point on the cathode with enormously high-current density. If the current could be kept from converging initially, then the discharge would persist as a glow for a long time with only perhaps a slight reduction in cathode drop, and the cathode would require a long time (order of one second for metals) before any melting would take place.

In 1921, the author conceived the idea of using materials of

* Communicated by the Author.

[1] JOUR. FRANK. INST., January, 1926, vol. 201, p. 79.

high resistivity as discharge electrodes. Obviously the high resistivity of the material would act to prevent current concentration at the cathode, since any such concentration of current would call forth a greatly increased ohmic drop.

Unfortunately all materials with high electrical resistivity have very much lower thermal conductivity than metals, but it was believed that in spite of this handicap, and solely because initial current concentration would be prevented, such materials would withstand the discharge for a larger time without melting or burning, and that the discharge would remain as a glow for a longer time.

A convenient high-resistivity material consists of a mixture of kaolin, carborundum, and lamp-black fired at a high temperature. By varying the proportion of lamp-black different resistivities may be obtained. The thermal constants of this material were measured and found to be

Specific heat,	$c = 0.185$ calorie per gram.
Density,	$\delta = 2.0$ grams per cm.^{3}
Heat conductivity,	$k = .016$ calorie/cm.^{2} per °C./cm.

The temperature rise at the surface of a cathode of such material will be, if W is the heat input per cm.^{2},

$$T = \frac{W}{4.18\sqrt{\pi k c \delta}}\sqrt{t} \tag{2}$$

and if $W = 2800$, this becomes

$$T = 4930\sqrt{t}. \tag{3}$$

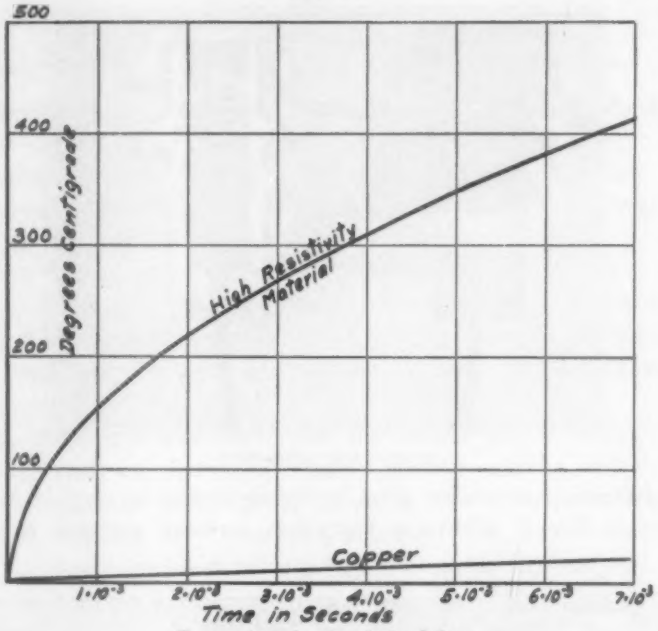
This is plotted in Fig. 1, where for comparison the curve for copper is also shown.

Resistance materials were cut into the form of discs, 1 inch in diameter, and tested in a circuit such as is shown in Fig. 2. A condenser C of two microfarads' capacity was charged up by a transformer and rectifier until the gap G' broke down. This took place at 2500 volts. The condenser then discharged through the test gap G, which had a spacing of 0.01 cm. The gap G was also connected to the 220-volt alternating-current main. R was a reactor to keep the condenser discharge out of the main.

Oscillograms were taken of the current, which would flow from the main after each condenser discharge. When the resistivity of the material in G exceeded 20 ohms per cm.^{3}, no current would flow from the 220-volt main across G, but if low-resistivity

material was used, an alternating-current arc would be maintained in *G*. The appearance of the discharge in *G* indicated that the

FIG. 1.



Temperature rise at cathode of glow.

resistivity was playing its part in preventing concentration of current, for the discharge would fill the whole gap for the high-resistivity materials.

This remarkable property of high-resistance materials at once

FIG. 2.

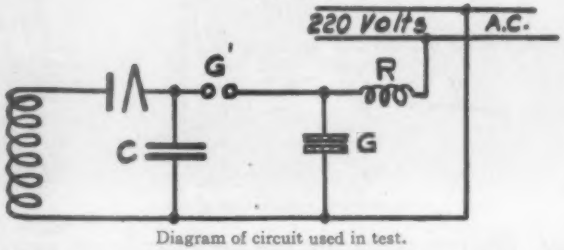
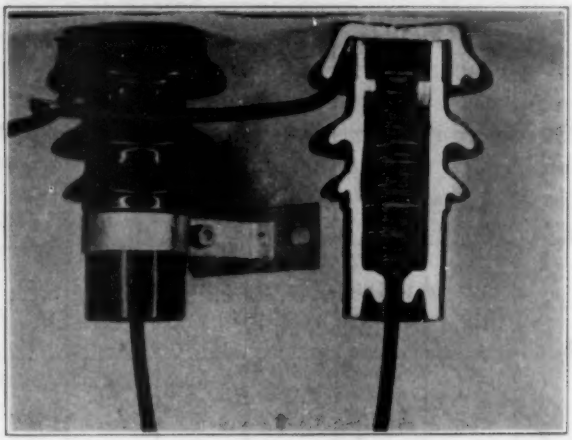


Diagram of circuit used in test.

found a technical application as a lightning arrester for power lines. Such arresters are now widely used on electrical distribution

and transmission systems. Discs of high-resistivity material, two inches in diameter and one-eighth inch thick, are stacked

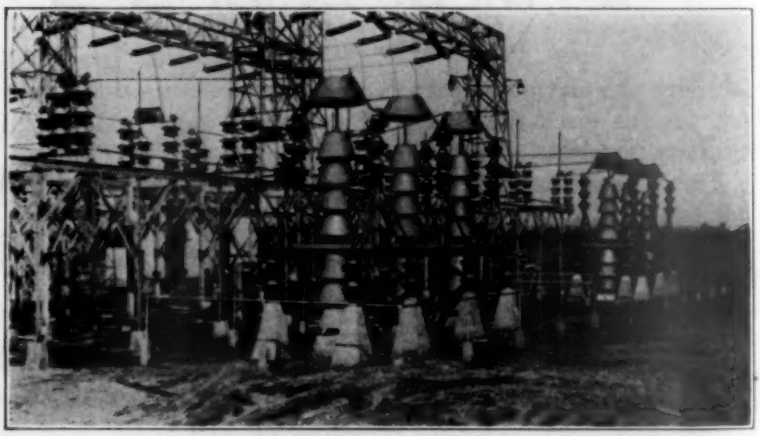
FIG. 3.



7500-volt pole type arrester.

into columns, successive discs being separated by .003-inch mica spacers. Fig. 3 shows a 7500-volt arrester suitable for pole

FIG. 4.



110,000-volt station-type arrester.

mounting. The porcelain case has been partly cut away to show the column of discs. Fig. 4 shows a 110,000-volt station type installation.

INDUCTIVE HEATING.*

BY

E. F. NORTHRUP, Ph.D.

Scientific Head, Ajax Electrothermic Corporation; Member of the Institute.

EVOLUTION OF IDEA THAT HEAT MAY BE DEVELOPED BY INFLUX OF ELECTROMAGNETIC ENERGY.

PREVIOUS to the period of Moissan it is probable that the conception of a white heat was tied to the idea of combustion. Anything that was visibly hot must be burning.

With the advent of electric heating came the conception that there could be a direct conversion of the new form of energy—that of the electric current—into heat and that very high temperatures need not be associated with chemical action. Electric resistance-heating resulted.

The discovery was made that the heated vapor between the white-hot ends of electrodes conduct electric current, but yet so resists its passage that a great elevation in temperature may be produced within a very restricted volume. The arc furnace was born. Moissan enclosed his arc in a box made of lime and succeeded in heating a considerable volume to a hitherto unknown temperature. He melted and reduced most of the refractory oxides. In every case, however, his resulting metal contained carbon and other impurities, for he added at his elevated temperatures to the masses heated not only energy, but material substances which came out of the vapors of the arc.

Some years later came the idea that the electromagnetic field is energy stored in space apart from all matter—in a vacuum even—and that if this field went out of existence an exactly equivalent amount of energy must appear elsewhere in one form or other. The energy of the electromagnetic field might become stored as potential energy in a dielectric, to appear again as electromagnetic energy, or it might be radiated into space as we observe it going from an antenna or it might become converted, in part at least, into localized heat.

It was shown that if the electromagnetic field moved into

* Presented at a meeting held Thursday, December 3, 1925.

solid matter of suitable conductivity, or if the field stood stationary and matter moved into it, some or all of the energy of the field would change over into heat-energy localized in the solid matter. It was a short step to show that by intercepting with conductive matter radiated electromagnetic energy, thereby changing it into heat and retaining most of the heat developed with a suitable heat insulator, a body could be raised in temperature without combustion or chemical action and without passing through it an electric current with the aid of electrodes. The utilization in practice of this conception produced the modern induction furnace. This evolution from the primitive idea that a white-hot body is something burning to the concept of a flow of energy from the medium outside into the mass to be heated, brings us close to full realization of what may be considered as the ideal method of heat production. A final extension of this ideal, however, would conceive that no limitation should be placed on the size or form of the mass to be heated. The mass should be capable of assuming the approximate shape of a solid cylinder, so that whatever is to be heated when brought into the molten state may be contained in a crucible.

The radiated energy which falls on a conducting mass to be heated passes readily through any jacket of heat-insulating material in which the mass is embedded, because the radiated energy here used is of long wave-length and all heat-insulating refractory materials are perfectly transparent to such radiation. When the radiated energy has entered the mass and been converted into heat, the short wave-length radiation given out from the hot body as radiated heat is mostly unable to pass through the heat-insulating jacket, because for short wave-length radiation a refractory heat-insulator is nearly opaque. In other words, long wave-length energy is radiated in and is unable to radiate out. Thus the heat accumulates and the temperature elevation may become very great.

Each time the energy of an electromagnetic field enters a conducting mass a certain fractional part of the energy of the field disappears as such and becomes heat in the mass. If this process is repeated one hundred times a second, the power—which is the rate at which energy is converted—is one hundred times as great as when the process occurs but once in a second. Thus

power, which appears as heat, is proportional to the electromagnetic energy in the field, to the fractional part of this energy which is changed into heat each time the field is developed and to the number of times in unit time that this happens. When the influx of the electromagnetic field occurs but 120 times a second, corresponding to the alterations for a 60-cycle circuit, the field must be a strong one and represent much energy, if any consider-

FIG. 1.

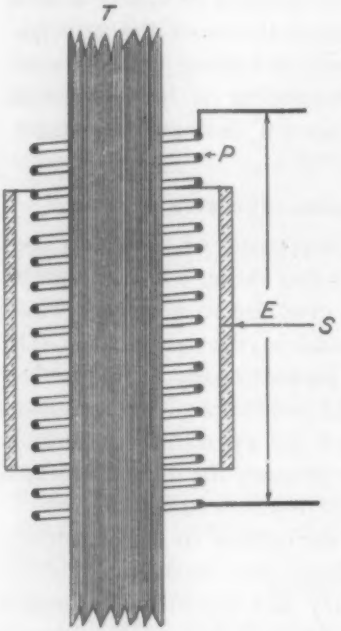
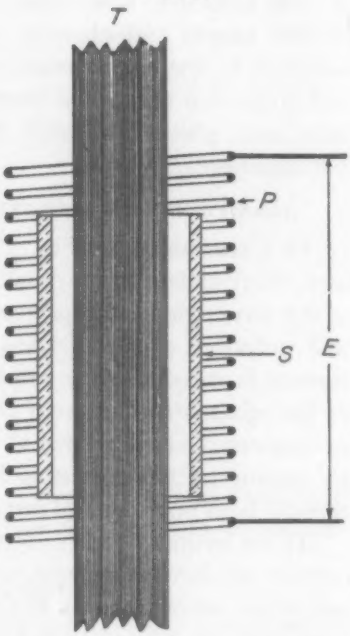


FIG. 2.



able amount of power is developed. An electromagnetic field is made strong and the energy stored in it becomes greatly increased when the magnetizing coil is filled with laminated iron. By means of iron it was found that so strong a field could be moved into a mass of conducting matter that much power would appear as heat in the mass, even though the electromagnetic field entered it at the slow rate of only 120 times a second. This idea developed into the type of induction furnace which uses transformer iron. In a furnace of this type in whatever form it may be constructed, the metal to be melted must form a ring or loop through which

the transformer iron must be passed. Otherwise stated, transformer iron interlinks with the melt and magnetizing coil.

By a simple and seemingly obvious extension of the above principle, it is seen that if the magnetic field is made to enter the mass to be heated ten times as often in a second, the field may be made one-tenth as strong and the same delivery of power may be obtained. By making the frequency greater all transformer iron may be omitted.

The principle, when thus stated, of ironless inductive heating is both simple and obvious. The applications of the principle, however, to the construction of successful heating units of small and large size demand a clear understanding of many electrical facts and phenomena and the successful devising of numerous appliances.

TRANSITION FROM IRON INTO IRONLESS INDUCTIVE HEATERS.

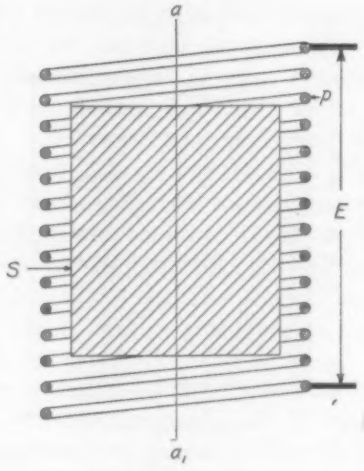
If a secondary S (Fig. 1), which consists of a single closed turn, surrounds a primary coil P, an alternating e.m.f. E applied at the terminals of the primary will give rise to a current which will induce a current of low potential in the secondary. The current in the secondary will heat it proportionally to the product of the square of the current and to the resistance of the secondary as measured circumferentially round the cylindrical secondary. By placing transformer iron T in the primary the induction which threads both primary and secondary is much increased thereby.

If the primary coil is wound on the outside of the secondary, current is likewise induced in the single-turn secondary and the induction which threads both primary and secondary is greatly increased, as before, when transformer iron threads through both secondary and primary.

If in this latter case the iron is removed, it is possible to change the secondary from a cylinder with a wall more or less thin into a solid cylinder S as shown in Fig. 3. An alternating current in the primary p will still induce circumferentially flowing current in the secondary which now consists of a solid cylinder. If the ampere turns in the primary are maintained the same as before the iron was removed, the induction which now threads through the solid cylinder, assumed non-magnetic, is very feeble as compared with the induction in the former case. The current

in the secondary is not only feebler, but the average cross-section of the circumferential path in which the current flows has become much increased and its resistance is low. The secondary, therefore, heats much less in this latter case in which no iron is used. The same heat as before is developed, however, in the primary coil and the power spent in heating the coil may equal or exceed that which appears as heat in the cylinder. The assembly, there-

FIG. 3.



fore, shown in Fig. 3, if used with current of ordinary frequency, would have a very low efficiency when considered as an inductive heating device.

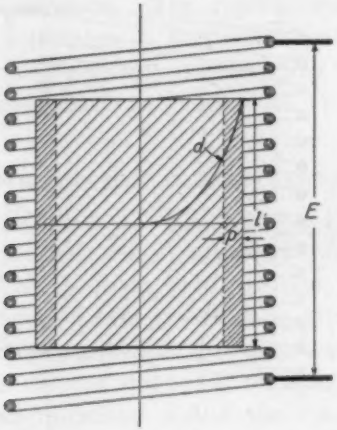
DEPTH OF PENETRATION.

Referring to Fig. 4, assume that we have the same assembly and same number of turns in the primary coil but that the applied frequency of the e.m.f. is increased, say, 100 fold. A phenomenon of vital importance now becomes manifest. The current induced in the solid cylinder is observed to diminish rapidly in current density as we move in from the surface toward the axis of the cylinder. Let the density of the current, as measured at varying distance, from the surface toward the axis of the cylinder be plotted as in curve *d* of Fig. 4. This curve is found to be a true logarithmic curve. If suitable relations maintain between the radius of the cylinder, resistivity of its substance and frequency of inducing current, we shall find that near and at the axis of

the solid cylinder the current density has become so reduced that we may assert no current exists there. In fact there would be no essential change in the flow of current or in the heating manifested if the axial portion of the cylinder were removed.

The total current through any conductor is the product of the average current density multiplied by the cross-section of the current-path. If we apply this rule to Fig. 4 and multiply the current density at the surface of the cylinder by a certain length p,

FIG. 4.



which will make the product equal to the total current in the cylinder, we arrive at a certain cross-section whose length is l, the length of the cylinder, and whose width is p. This cross-section, in its resistance to the flow of the total current, is equivalent to the actual resistance of the cylinder. The length p is called the "depth of penetration" of alternating current into the cylinder. At a depth three or four times the depth of penetration no appreciable current and no heating exists in the cylinder. As was shown by Steinmetz, when the frequency and resistivity of the material of the cylinder is known, the depth of penetration may be calculated. It decreases directly with the square root of the frequency and inversely with the square root of the resistivity of the substance of the cylinder.

It is but a single step from the assembly indicated in Fig. 4 to an ironless high-frequency induction furnace of crucible form which can be adapted to melting metals with high efficiency in the

ordinary type of crucible and to automatically stirring them when molten.

In Fig. 5 the magnetizing or inducing coil surrounds a crucible which contains conductive material M to be melted. When the applied voltage E is chosen of sufficient frequency, the depth of penetration p is slight and the effective cross-section of the current-path in the metal is small. This is indicated by the shaded portion s in Fig. 5.

Returning to our viewpoint that electromagnetic energy is all that enters the melt, we see that, consistently with the above description of the phenomenon of ironless inductive heating, this energy begins to be converted into heat as soon as inflowing energy reaches the surface of the melt and that no electromagnetic energy, as such, is found at the axis of the mass.

Not all of the electromagnetic energy associated with the inductor, especially that which exists in the medium exterior to the mass and interior to the inductor, is used up as heat. The remainder is given back to the circuit. The condenser C (Fig. 5) is joined across the line to receive and store up this energy where for a time it is held in potential form.

If the condenser is chosen of right capacity, the power factor of the combination, furnace and condenser, is unity.

It is of vital importance to ironless inductive heating that the microfarads required thus to bring the power factor to unity is less in exact proportion as the frequency is higher.

In making the transition from low-frequency inductive heating, in which transformer iron is used to increase the induction, to high frequency using no iron, we have secured among many other results the following:

We have dispensed with the necessity of making into ring-form the substance to be heated in order that iron may be passed through it. We are, therefore, largely unlimited in our choice of the shape of what we heat, and we can use an induction furnace of crucible form having many advantages over a ring-type induction furnace, one of which is minimum radiation surface for a given volume.

We have used a weak field moving into and out of the mass rapidly and by so doing have secured the same rate of change of induction as may be obtained with a strong induction, gotten with the aid of iron, which moves into and out of the mass slowly.

We have reduced the microfarads employed, and hence the cost of condensers needed to raise by a given amount the power factor. We have done this in just the proportion that we have increased the frequency.

By reducing to a minimum the area through which heat developed can escape, we have made it possible to obtain an almost unlimited temperature elevation.

To fully realize the possible accomplishments listed above several very basic principles must be held in view and applied. These we list as follows:

Under the most ideal conditions only a fractional part of the energy of the electromagnetic field which builds up around the inducing coil is converted into heat. The energy left in the magnetic field after the portion converted into heat is subtracted is returned either to the generator of the energy, or it must be stored for a time in the dielectric of a condenser as potential energy in an electrostatic field. Thus the generator and the condenser taken together must have sufficient capacity, that is, be large enough, to store up for a period of one-half cycle of the alternating current all electromagnetic energy not converted into heat, and the generator must have an additional capacity sufficient to supply that portion of the electromagnetic energy which becomes converted into heat. If the microfarad capacity is chosen of right value to store all unconverted energy, then the generator need only be large enough to supply that portion of the energy which is converted into heat and is not returned to the circuit.

The investment cost for equipment to supply power for inductive heating will be, *in every case*, a sum made up of two costs; that of apparatus to supply the power component of the product, volts × amperes or converted power, and of apparatus to store once in every half-cycle the reactive component of same, or unconverted power. There is no escape from the conclusion of this generality whatever devices may be employed for inductive heating with or without transformer iron.

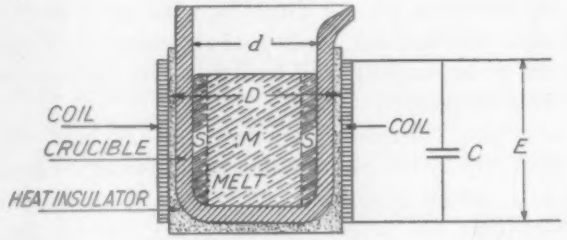
A certain portion of the electromagnetic energy, associated with the inductor, enters the mass through its surface to become converted into heat. The unconverted electromagnetic energy, in addition to that portion which fails to enter the mass, is returned as such to the circuit and this unconverted energy must be stored either in a condenser or flow back into the generator.

If it flows back into the generator, this must be made in every case large enough to take care of it.

The coil in and about which the magnetic field has developed possesses necessarily ohmic resistance, which happens to be higher for alternating current than for direct current. When the energy of the electromagnetic field is rising from zero to a maximum, a certain portion of it is converted into heat in the coil itself and for the purpose of heating the mass is wasted. Thus the heating efficiency of the device can be made high only by maintaining the wasted portion of the energy small.

The employment of a highly specialized method to obtain an important result is often justified for use in the laboratory even

FIG. 5.



though the cost of equipment and operative cost are both high. If, however, the same general method is to be extended to industry, economic features assume an importance equal to or greater than technical. It appears on analysis that the underlying questions of the economic value of inductive heating on a large scale are these: Can the reactive component of the energy of the electromagnetic field be stored at less investment cost in a dielectric than in the generator itself and can this investment cost for ironless inductive heating be made low enough to justify its wide adoption? We believe that both these questions have been answered in the affirmative. Thus, if we use for ironless inductive heating a frequency which we may assume as eight times the frequency of the supply circuit, the power factor at the generator terminals can be raised to unity with exactly one-eighth the number of microfarads of condenser that would be needed if the line frequency were supplied directly to the inductor. So, by the simple device of raising the frequency supplied to our furnace from 60 cycles to 480 cycles, we cut down the cost of our

condensers to about one-eighth, it being assumed that the power factor to be raised is the same in the two cases.

DESCRIPTION OF A TYPICAL ASSEMBLY.

Fig. 5 shown above may be taken to represent a typical assembly for melting a large batch of metal by high-frequency induction. We have made no attempt to show details of construction, as features of design have no place in this presentation, which is intended to be a consideration of general and basic principles only.

Attention is, however, directed to the type of inductor coil which analysis and experience have shown to be best adapted for induction by high frequency. This coil, in Fig. 5, is always wound in a single-layer winding. Copper is used for the winding in the form of either a hollow, flattened copper tube or a solid copper strap which is several times as wide as it is thick. The former is used where water cooling of the inductor is desired and the latter when air cooling will suffice. The flattened copper is always wound edgewise.

The so-called "coupling" between the coil and the melt is determined chiefly by the ratio; square of diameter of melt divided by square of diameter of coil.

In order that the largest possible portion of the electromagnetic energy associated with the coil may enter the melt, it is important to keep the coupling as high as possible, namely, the coil should fit around the melt with the least possible clearance. On the other hand, the heat which is given to the melt should be retained as well as possible by heat insulation around the crucible in the space between crucible and coil. These two requirements, close coupling and good heat insulation, conflict, and it is the task of the designer to make the best compromise possible in order to secure highest power factor and good efficiency.

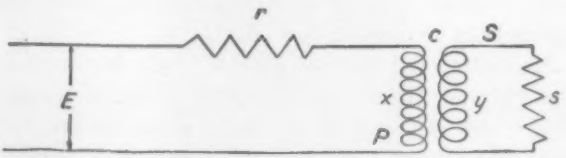
EQUIVALENT CIRCUITS.

Every high-frequency induction furnace comprises the electrical circuits shown in Fig. 6. The primary P of a coreless transformer shown in these circuits has both ohmic resistance r and reactance x. Likewise the secondary S, which is the mass to be heated, has reactance y and ohmic resistance s. The primary is coupled to the secondary by a degree of coupling C which depends chiefly on how close the coil is wound round the melt.

For every pair of coupled circuits like those shown in Fig. 6 there exists a single equivalent circuit which is represented in Fig. 7. In this single circuit, R stands for all the resistances and X for all the reactances of the combination shown in Fig. 6. If R and X are assigned correct values and i is the value of the current through the furnace coil, i^2R will be the power component and i^2X the reactive component of the volt-amperes supplied to the furnace terminals.

It is in most cases possible to determine by calculation both

FIG. 6.



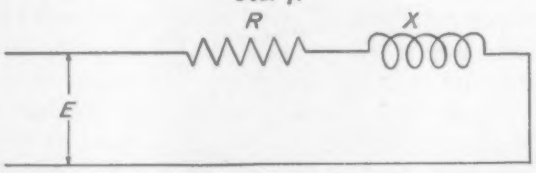
R and X from a knowledge of ascertainable quantities. When both R and X are known, the electrical characteristics of the furnace are readily found by very elementary rules of procedure.

SOME LEADING FEATURES OF HIGH-FREQUENCY INDUCTION.

A summary of the chief characteristics of high-frequency induction are:

(*a*) Energy and energy only enters the mass to be heated—

FIG. 7.



which may have the form of a solid cylinder—by way of that portion of its surface which is covered by the coil.

(*b*) If the condition is met that the mass have proper size and resistivity, all of the inflowing energy is converted into heat within it.

(*c*) The ratio of the power component to the reactive component is determined chiefly by the coupling. In other words, close coupling and high power factor go together.

(*d*) The efficiency of an ironless inductive furnace is quite

equal theoretically to that of an induction furnace which uses transformer iron. The electrical efficiency of the ironless induction furnace may be made about the same for furnaces of different sizes, though the melting efficiency of large furnaces may become considerably greater than that of small furnaces.

(*e*) The successful functioning of the ironless induction furnace depends largely upon the property of insulators that long wave-length electromagnetic radiation passes through any heat insulator without hindrance into the mass, while short wave-length heat radiation escapes from the mass with difficulty. Because of this, heat accumulates in the mass and extremely high temperatures may be obtained.

(*f*) All molten conducting matter when acted on inductively automatically stirs. In the high-frequency crucible-form of induction furnace the stirring takes place in a unique way. Thus when alloys are melted the constituents mix thoroughly.

(*g*) Inductively heated matter when molten is a mass having uniform temperature throughout. Hence volatile constituents of alloys are not expelled at hot-spots as in arc furnaces.

(*h*) The speed at which the temperature may be raised throughout a mass by inductive heating may be increased almost without limit, because the rate of flow of energy into a mass is independent of the production of a temperature gradient from without inward.

(*i*) In all inductive heating the temperature gradient is from the mass heated outward. Hence in ironless inductive heating the melt or molten bath is always the hottest part of the furnace.

(*j*) Since no material substance (as vapor from an arc) enters or leaves the mass heated—energy only flowing—the means is here offered of obtaining throughout a mass of large volume an extremely high temperature without any chemical contamination of the product heated.

Additional practical features pertaining to a large induction furnace are:

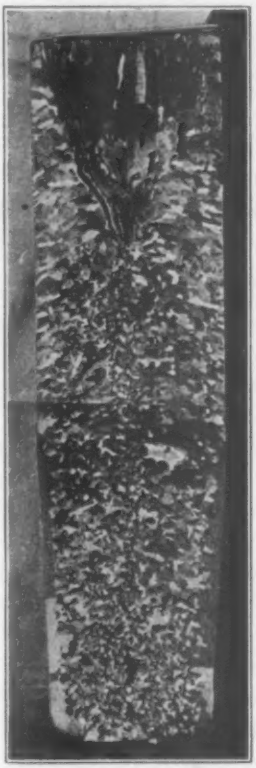
The electrical efficiency is almost independent of the resistivity of the metal melted, within extremely wide limits. Thus the same furnace will melt either electrolytic copper or nickel-silver with about the same electrical efficiency.

The power may be turned off a full furnace after its charge is melted, this being allowed to solidify and become cold; when

the charge is remelted no injury to container or crucible results. Ferrous metals are melted equally well with non-ferrous metals, though a somewhat higher frequency is generally required for the former when the melts are not large.

The melting unit can be constructed of any size desired, and

FIG. 8.



Westinghouse carbon-free nickel-iron billet, 225 lbs.

when the number of kilowatts supplied is increased proportionally with the weight of the charge, the melting efficiency of the furnace improves with its size, likewise its power factor. The method, therefore, becomes applicable to installations of the greatest magnitude. A favoring circumstance of large installations is that the investment cost per ton to be melted greatly decreases with the tonnage to be handled.

Ingots cooled in the furnace do not "pipe" if the power is

shut off gradually while the metal is solidifying. This is shown by the reproduced photograph (Fig. 8) of an ingot of nickel-iron alloy which weighs 225 pounds. This ingot shown in section by the photograph was made by the Westinghouse Company in a high-frequency induction furnace. The alloy is 50 parts electrolytic nickel and 50 parts electrolytic iron. The many melts made are said to contain less than 0.006 per cent. carbon. The walls of the few gas holes which occur near the top of the ingot are free from oxide and weld together under forging operations. Hence no metal need be lost by trimming.

TECHNICAL FACTORS WHICH DETERMINE CHOICE OF FREQUENCY.

The technical consideration which determines one's choice of frequency, N is that a certain relation shall exist between the diameter of a cylindrical charge and its resistivity.

It has been found by analysis that when $N \geqq \frac{25 \times 10^8 \rho}{D^2}$ the technical requirement is met most advantageously. In this relation ρ is the resistance in ohms between opposite faces of a centimetre cube of the material and D is the diameter in centimetres of a cylindrical charge to be melted.

Thus yellow brass has, when molten, a resistivity of about 40×10^{-6} ohms. If a frequency of 480 cycles is to be used, the above relation shows that a cylindrically shaped charge should be not less than about 14.5 cm. or say 5¾ inches in diameter. It may be much greater than this if desired.

If steel is to be melted, we may assume a resistivity, just before it becomes molten, of $\rho = 10^{-4}$ ohms. If the frequency to be used is 2000 cycles, the diameter of the cylindrical charge should not be less than about 11.2 cm., or say 4¼ inches. It may be as much larger as may be desired.

Now let us assume that it is required to melt pure iron in a crucible which has an inside diameter of only 2.5 cm. The above relation enables us to calculate that an optimum frequency to use would be about 40,000 cycles. We should note, however, that the melt is of such small size that it is unnecessary to use any considerable amount of power. Thus, where the melts are small and high frequency is indicated, there is seldom a demand for the use of much power and when the melts are large and there is demand for much power, it is not necessary to use a very high frequency.

When the technical requirement in a particular case demands a frequency of say 20,000 to 100,000 cycles, the best device for giving such frequency is the discharge-gap oscillator or high-frequency converter, as it has been called. On the other hand, a commercial demand where 100 pounds or more of metal are to be melted, being fully met on its technical side by frequencies in the range 500 to 2000 cycles, makes the ordinary motor-driven generator the best device for supplying the power. In considering the installation of a motor-generator set we have only then to consider a choice of frequency which is based on minimum cost of investment. This is an intricate subject, but it is assumed that with prices which prevail in the United States a frequency of 480 cycles, while sufficing technically, is the most economical frequency to employ for all ordinary cases of commercial melting of non-ferrous metals and likewise for melting ferrous metals where charges of several hundred pounds are involved. For smaller melts of ferrous materials as much as, but not more than, 1800 cycles is the frequency which will best meet both technical and economic requirements.

OSCILLATORS.

The type of high-frequency oscillator which has been found best adapted to energize small furnaces, where the required frequency is from 10,000 to 100,000 cycles, is the ordinary Tesla oscillator equipped with a mercury discharge-gap. Very high-frequency alternators of the inductor type, vacuum valve-tube oscillators, and the Poulsen arc oscillator have all been considered and rejected in favor of the discharge-gap oscillator.

Whatever device is used for the conversion of line frequency into the needed high frequency, a certain amount of condenser is required to store up the reactive component of the energy in every case. The discharge-gap oscillator employs in addition to this necessary amount of condenser a minimum amount of additional apparatus and costs the least.

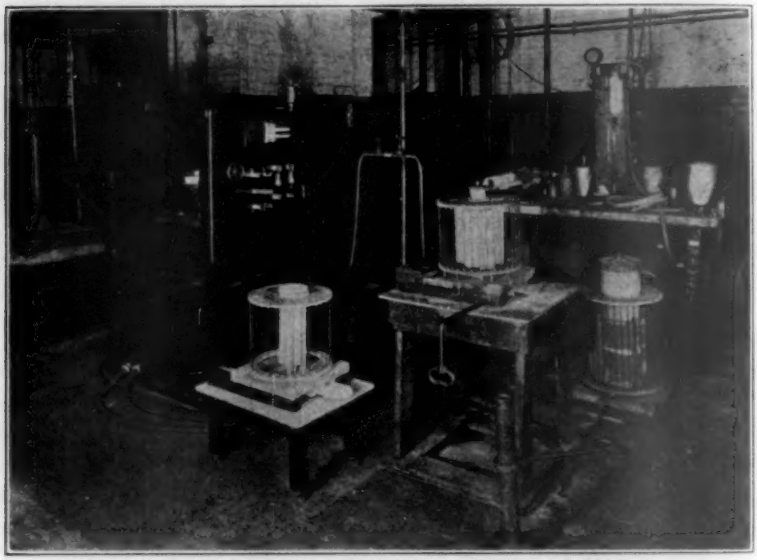
The discharge-gap oscillator differs in principle from the Tesla oscillator only in that the potential induced in the secondary is stepped down to give heating effect instead of being stepped up to give discharges through a long air-gap.

There are physical limits which make it impracticable, if not impossible, to construct single-phase oscillators which will deliver

more than about 20 kw. to the terminals of a furnace. There are in existence approximately 130 oscillators supplied with a transformer rated at 35 kv-a. One of these oscillators is capable of delivering about 17 or 18 kw. to its load. A typical installation of one 35-kv-a. oscillator is illustrated in Fig. 9.

In this type of oscillator electricity is stored up in a single condenser-bank or preferably in two condenser-banks, one on each side of the line and hence in series. When the condensers

FIG. 9.



Ajax-Northrup oscillator and furnaces in the Bell Telephone Laboratories, Inc.

become charged to a sufficiently high potential, the discharge-gap ruptures and the condenser empties with a rapidly dying-out oscillatory discharge. The furnace coil is in circuit and there flows through it at each condenser-discharge a high-frequency current which diminishes in magnitude with the time. This is the inducing current which acts upon any conducting mass within the coil to heat it. These oscillatory discharges recur at frequent and regular intervals. The frequency of the oscillations depends upon the capacity and inductance in the circuit. Since the inductance changes with furnaces of different size and type used with the oscillator, the frequency is different with different furnaces.

A small furnace which requires a very high frequency will have current of high frequency delivered to it. A larger furnace which requires less frequency will have current of lower frequency delivered to it. Thus, to a certain extent, the frequency automatically adjusts itself to the requirements of the furnace.

When using oscillatory currents for heating, we may introduce a somewhat different conception of energy-transfer than that given above for high-frequency sine-wave currents. Thus, each time the condenser is charged it becomes a localized storage place of electric energy in the form of a stress in the dielectric. When discharge occurs this energy is released and changes into electromagnetic energy stored in the medium in and about the coil. At each swing of the electricity a certain fraction of this electromagnetic energy is converted into heat within the mass inside the coil, the remaining portion changing back into energy of the potential form stored in the condenser. Eventually, whether the conversion of electromagnetic energy into heat during a half-oscillation is much or little, *all* of the energy originally stored in the condenser is used up. The condenser then recharges and the process of energy-conversion is repeated.

To obtain good efficiency in heating the mass, the greatest possible fraction of the energy stored in the condenser must be converted into heat within the mass only and the least possible fraction in the leads, in the discharge-gap, in dielectric losses in the condenser, in radiated energy and in heat developed within the coil itself. Consideration of the design details to be observed in order to accomplish this result do not belong to this general survey.

GENERAL APPLICATIONS OF HIGH-FREQUENCY INDUCTIVE HEATING.

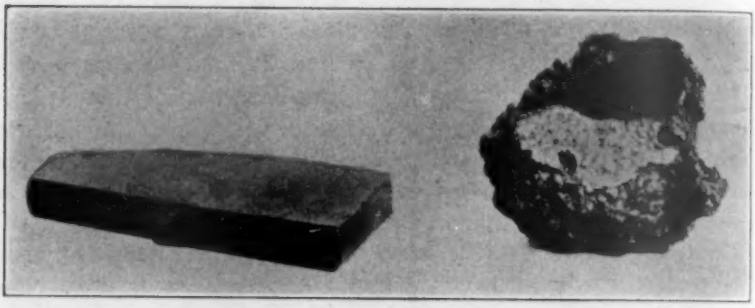
(1) *Using Oscillators.*—There are few, if any, applications of high-frequency inductive heating where one would choose to obtain the high-frequency current by the use of oscillators if the power requirement for a single unit is to exceed about 25 kilowatts.

As most research work in laboratories is done with comparatively small amounts of power, the high-frequency oscillator is the least expensive, most simple and altogether satisfactory device for every kind of laboratory research work with very high temperature, especially when complete control of the chemical purity of the product is necessary.

Thus tantalum, which fuses at about 2900° C., may be melted carbon-free as illustrated by the melt shown in Fig. 10.

The high-frequency oscillator has been used in multiple units for the production of a large tonnage on a commercial scale of ferrous alloys where great purity and freedom from carbon in the product was required. One plant in England has operated forty-two of these oscillators at the same time, each making 18-pound melts of nickel-iron alloy for use in submarine cables.

FIG. 10.



Tantalum, before and after melting, carbon free.

Fig. 11 shows a view of a row of thirteen of these oscillators, each with its 18-pound furnace standing on the floor before it. This installation was made only in preference to an installation of a few large furnaces deriving current from a 2000-cycle alternator, because at the time of the installation the alternator could not be secured in the short time required.

Following is a curtailed list of specially indicated uses of a high-frequency oscillator:

(1) For heating the interior parts of evacuated bulbs, also for melting small masses in vacuum.
(2) For melting the highly refractory costly metals and alloys when complete freedom from carbon is necessary.
(3) For making a heat treatment of small masses of ferrous material or portions of larger masses.
(4) For graphitizing small blocks of carbon.
(5) For heating metal in relatively thin sheets.
(6) For melting the precious metals used in the jewelry trade.
(7) For producing a black-body temperature up to the temperature at which carbon will graphitize throughout a volume as large as one-fifth of a cubic foot.

(8) For all kinds of laboratory investigations where temperatures are required which exceed those obtainable with the resistance-type of furnace and where chemical control of the product is necessary.

(2) *Using Motor-driven Generators.*—In the case of oscillators the seat of e.m.f. is not in the oscillator which serves only to convert line-frequency into high frequency. In the case of an alternator the seat of e.m.f. is in the alternator which supplies

FIG. 11.

Thirteen of forty-two oscillators and furnaces used in producing a carbon-free alloy for submarine cables.

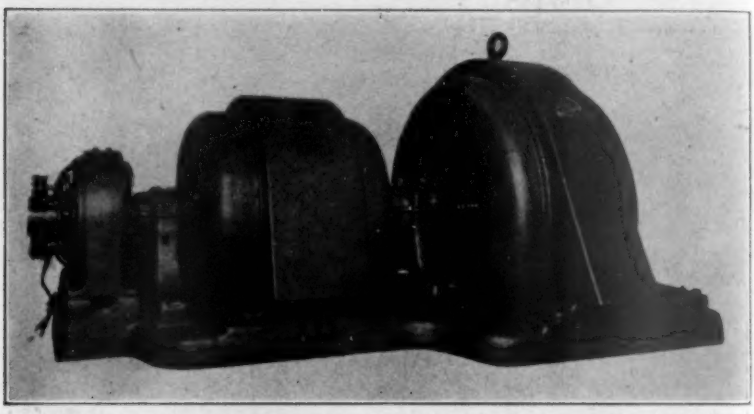
the high-frequency current and which supplies it as a pure sine-wave current.

The large field for high-frequency inductive heating is the industrial field and here alternators must be used to supply the power. Since the overall efficiency of a 600-kilowatt motor-generator set where the generator gives 480 cycles reaches as high as 87 per cent., and since the theoretical electrical efficiency of a properly designed furnace is about 90 per cent., we have the possibility of inductively heating large masses with an overall electrical efficiency of about 78 per cent. The cost for equipment

is not prohibitive. The field of usefulness, therefore, which we may hope to cover is extensive.

Fig. 12 is a photograph of a motor-generator set made by the General Electric Company for ironless inductive heating. The generator is rated at 600 kw. It supplies current of 480 cycles at 1800 volts and is driven by a synchronous motor. Two of these machines have been placed in service for supplying current to twelve 100-kw. furnaces to be used for melting nickel-silver.

FIG. 12.



G. E. 480-cycle, 600-kw. motor-generator set. One of two in service for melting nickel-silver.

Fig. 12*a* is a view of a condenser-bank of 36 units used to correct the power factor of a 100-kw. furnace.

Since the field of application is conceivably very extensive, only the merest outline can here be given of the suggested commercial uses to which this method of heating may be put.

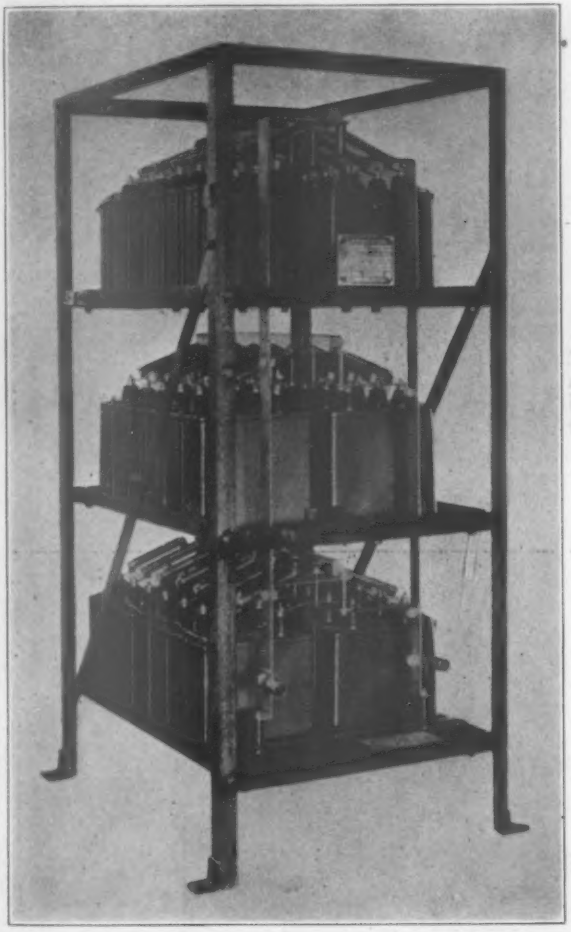
(1) Melting of the non-ferrous metals and alloys of industry, such as brasses, bronzes, pure aluminum and aluminum alloys, pure silver, pure copper, nickel-silver and resistance alloys.

(2) In the ferrous field pure carbon-free electrolytic nickel and iron, singly or alloyed, and high-grade steels as magnet steels, tool steels and stellite.

(3) An application of which little use has thus far been made but which promises to have a future is the heating without melting of steel for forging, rolling, etc., when in the form of steel rods and billets, steel pipe, etc., in those cases where the diameters are sufficient to make a frequency of 2000 cycles or less applicable.

The above commercial field may be covered with current supplied by alternators of sizes and giving frequencies as follows:

FIG. 12 a.

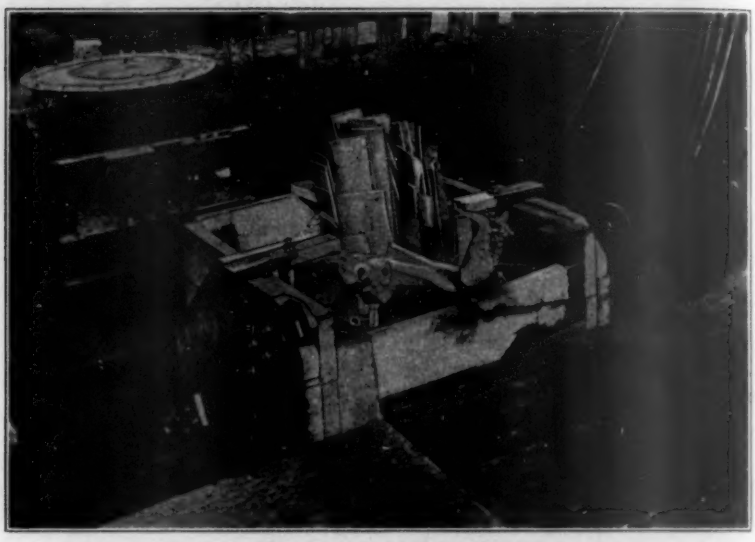


Rack of G. E. capacitors for power-factor correction.

For the non-ferrous field 480 cycles obtained from units rated at 50, 100, 150, 200, 300, or 600 kw.

In the ferrous field 1800 cycles would be chosen as the frequency for machines up to a capacity of about 150 kw. and for machines of greater kw. rating 960 or 480 cycles would suffice.

FIG. 13.



700-lb. furnace charged with slabs of pure copper.

FIG. 14.

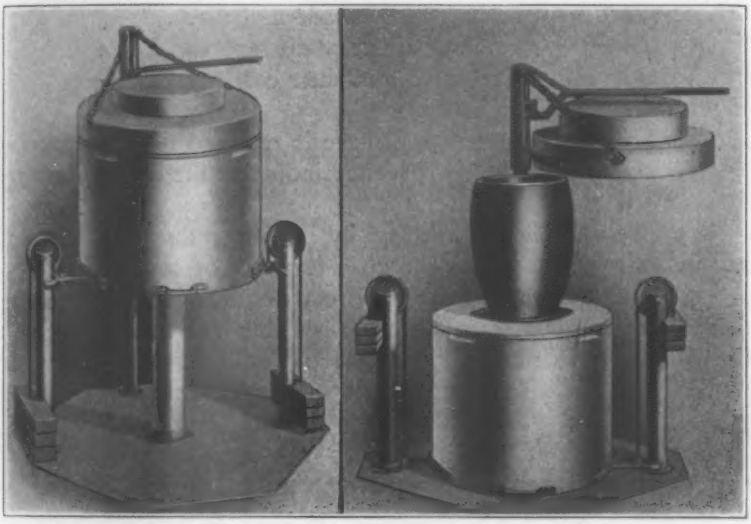
Same charge shown in Fig. 13 being poured.

These latter machines would be equally well adapted to the ferrous and non-ferrous fields.

It is thus seen that we enter the commercial field of metallurgy with high-frequency generators of various sizes from 50 kw. up and built for two or three frequencies only to cover all cases, namely, we can accomplish commercial high-frequency inductive heating by increasing line-frequencies either eight, sixteen or thirty times.

An especially attractive field for 480-cycle inductive heating

FIG. 15.



Up and down position of "drop-coil" furnace.

is melting in crucibles non-ferrous metals for casting shops, also non-ferrous metals which are to be wrought. Figs. 13 and 14 show typical installations which have been made.

A recently developed type of furnace for making 175-pound melts of brass for use in brass-casting shops has been termed the "drop-coil furnace." Two views of this type of furnace appear in Fig. 15. When the coil is in the down position, the crucible may be lifted off its support with tongs and carried to the molds.

FUTURE OF INDUCTIVE HEATING WITH MEDIUM HIGH FREQUENCY.

The present installations of ironless inductive furnaces using current obtained from motor-generator sets are too few and the

method is too new to predict future extensions. It may be asserted with confidence, however, that the extension which will come will be determined chiefly by economic considerations because on its technical side the method of ironless inductive heating has already demonstrated its great superiority and its extreme versatility.

It is always pleasant to prophesy and those desiring to indulge in this form of mental relaxation will be helped toward making reasonable prophecies if they keep in mind the following fundamentals:

(1) The melting efficiency of furnaces increases rather than decreases with size and no limitation is in sight for the size of furnace which may be practically made and used.

(2) Generators of the necessary current can be built in as large units as may be required and their cost per kw. rating falls off with their increase in size.

(3) The crucible-type of furnace is restored to electric melting which makes the high-frequency inductive method the friend of the crucible manufacturer.

(4) The efficiency of melting by ironless induction compares very favorably with the best electric furnaces of other types.

(5) For the first time in the history of fuel or electric melting of ferrous materials does it become possible and feasible to melt large quantities of metal in crucibles and without the presence of any carbon and with perfect control of chemical composition and speed of melting.

(6) The circuit which supplies the high-frequency power operates at substantially unity power factor and the load on the motor which drives the generator is very steady, of high or unity power factor and is in all respects the ideal load from the viewpoint of the station man.

(7) The reactive component of the power is taken care of with condensers which, in the way used, are inherently much less costly than generators made of sufficient excess size to accomplish the same purpose.

A SINGLE STRAIGHT CONDUCTOR AS A NEW FUNDAMENTAL. A REJOINDER.

EDITOR,
JOURNAL OF THE FRANKLIN INSTITUTE,
Philadelphia, Pennsylvania.

SIR:

I note that in addition to the paper by Doctor Hering which appeared in the February, 1925, number of your JOURNAL, you have published another paper by him in the December, 1925, number. In both of these papers he presents an erroneous formula for the magnetic energy per unit length of a straight current. The train of argument by which he obtains this formula seems to be somewhat as follows:

Consider a very large rectangular circuit in a vertical plane, the upper portion of which is connected to the lower portion by means of two mercury cups. Allow the upper portion to rise 1 cm. The work done by the pressure induced in the liquid mercury by the electromagnetic forces is i^2. Kelvin's law requires the energy of the magnetic field to increase by an equal amount. Hence the energy associated with one centimetre of each vertical wire is $1/2\, i^2$.

There are two errors in this "proof." First, the force F on the upper horizontal wire due to the magnetic field is neglected; second, Kelvin's law is not strictly applicable in the form in which Doctor Hering uses it to a circuit containing a liquid conductor as here arranged. The second error will not be stressed since it is less consequential than the first. But the neglect of the force on the upper wire leads to results which are not even approximately correct. If the height of the rectangle is taken large compared with its width, this force can easily be calculated to a first approximation, and is found to be

$$F = 2i^2 \log \frac{l}{a},$$

where l is the width of the rectangle and a is the radius of the wire. Therefore the work done for a unit displacement is

$$i^2 + 2i^2 \log \frac{l}{a},$$

and on the assumption that Kelvin's law holds, the energy per centimetre of each of the vertical wires comes out

$$w = i^2\left[\frac{1}{2} + \log\frac{l}{a}\right].$$

If, for instance, the radius a of the wire is 0.2 cm. and l is 200 cm., Hering's formula is in error by roughly 1400 per cent. The Hering formula can be tested by a simple experiment which the present writer has recently performed.[1] The circuit used in this experiment is essentially the same as that here described. The experimental measurements confirm the formula given by the present writer and are 900 per cent. greater than indicated by Hering's formula.

It has been shown that Hering's theory is erroneous and that his formula is not in accord with experimental measurements.

SLOANE PHYSICS LABORATORY, LEIGH PAGE.
YALE UNIVERSITY, New Haven, Conn.

International Geological Congress.—Announcement is made of the Fourteenth International Geological Congress which will convene in Madrid, Spain, in May of the present year. It is estimated that at least 1000 delegates including the most eminent geologists and engineers from Great Britain, Belgium, Denmark, Cuba, Mexico, Bulgaria and the United States will be present. Prior to and immediately following the Congress there will be excursions to Sevilla, Cordoba, the Canaries, Catalonia and the Balearic Islands. The Inaugural Session of the Congress will be held on May 24th and will be opened by His Majesty, Alfonso XIII, King of Spain. A considerable number of papers to be presented at the meetings of the Congress have already been submitted and material of this kind should be forwarded before April 1st next.

Effect of Low Temperature on Hens' Eggs.—T. MORAN (*Proc. Roy. Soc.*, London, Series B, 1925, 98, 436–456) has studied the effect of low temperatures upon hens' eggs. Freezing and thawing cause the white of the egg to separate into a fluid portion and a viscous portion. Freezing and storage at a temperature below –6° C., followed by thawing, cause the yolk of the egg to lose its normal fluidity, and to become a stiff paste. The lecitho-vitellin, a highly complex conjugated protein of the yolk, apparently, is precipitated by the freezing, and does not redissolve on thawing. These changes are of practical importance, since frozen whites, yolks, whole eggs, and mixtures of these in various proportions are manufactured in enormous quantities for use in the food industries.

J. S. H.

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[1] *Am. Jour. Sci.*, 10, 398, 1925.

NELA RESEARCH LABORATORY NOTES.*

ON ACTIVE NITROGEN.

By Richard Rudy.

DISCHARGE tubes were sealed to containers of 20 or 30 cm. diameter filled with nitrogen at a few millimetres pressure. When a short, strong discharge was passed, the entire bulb was filled with yellow afterglow which could be seen for over fifteen minutes. The rate of decay of the afterglow (during the first few minutes) increased with increasing nitrogen pressure to about the same extent as the fluorescence of mercury vapor was weakened after addition of other gases. At pressures lower than about 1 mm., it was usually more difficult to obtain bright glows. At all pressures (up to about 15 mm.), and also when argon was added, the decay followed a bimolecular law. By connecting a long tube surrounded by a furnace with a discharge tube, it was possible to study the increase in the rate of decay with temperature; it was necessary to increase the temperature by about 100° in order to double the rate of decay in the tube. A magnetic field of over 500 gauss had no influence upon the glow. One of the bulbs was sealed off a year ago when the experiments were interrupted; on recently starting the first discharges in these bulbs the afterglow was very faint, but increased rapidly when the current was passed for some time. A spectroscopic study of the afterglow discharges has shown a complete absence of nitrogen lines from the atom.

Active nitrogen has sometimes been described as atomic nitrogen, its energy being due to the recombination of the atoms (law of decay). It is difficult to explain, however, why no lines due to the atom of nitrogen were found in the afterglow or in glowing nitrogen through which a discharge was passed. The fourth positive group must be present (the *o, o* line of this group requires 14.8 volts, part of which, however, is used up to bring the atoms further apart), and it is true that this system is due to loosely bound atoms in a molecule, but the molecule may break up into ions rather than into atoms. The nitrogen molecule probably has

* Communicated by the Director.

the same number of outer electrons as the neon atom and resembles it in its stability and inertness. It may then be assumed, as has been done, that the N_2 molecule exists in metastable states, having an energy equivalent to about 11 volts in analogy with the neon atom. The work on ionization of N_2 by electron impacts makes the existence of metastable molecules very probable. There is further no doubt that the neon atom can persist for about 4/1000 of a second in the metastable state, but this period does not explain the afterglow duration unless by a collision the energy of electronic excitation is transformed into vibrational energy (which the neutral atom cannot radiate). Strongly vibrating molecules could react quickly with impurities present or cause dissociation. The N_2 molecule can also retain considerable quantities of energy when emitting the band systems. Strutt's spectrograms, and more clearly the careful work of R. S. Mullikan, shows that band spectra excited by active nitrogen show vibrational energy as if they had been produced at high temperatures (whereas the rotation of the atoms corresponds to the usual temperature). With its strongly vibrating atoms the active nitrogen has somewhat the nature of a solid body and an influence upon the adsorption on solid surfaces might be expected. However, experiments made after the glow had been shut off from the discharge tube failed to show a change in adsorption, owing very probably to the small concentration. It is known that active nitrogen excites a number of solid bodies to emit light. The energy to excite the afterglow bands is about 11.4 volts.

When an evacuated vessel is connected by a stopcock to a discharge tube filled with active nitrogen and the stopcock is suddenly turned, the active nitrogen rushes into the evacuated space as a yellow " jet." It might be helpful to study the escape of a gas through nozzles of different shape from a space at a few mm. (or cm.) pressure into a vessel where a much smaller pressure is maintained.

ON THE LOW-VOLTAGE ARC IN MERCURY VAPOR.

By Richard Rudy.

EXCITED mercury atoms ($2p_2$) may cause other atoms to emit light; this radiation is greatly enhanced if other gases, *e.g.*, N_2 or A, are present (Donath, Wood). During the collisions the argon probably brings the excited atom from the $2p_2$ to the

metastable $2p_3$ state and thus increases the chance of energy transfer, of ionization or absorption. This effect was studied in the low-voltage arc between an incandescent tungsten ribbon and a mercury anode at from 4 to 12 mm. distance.

When mercury alone was present, the saturation current was well marked at lower filament temperatures, but masked by increasing ionization for stronger electron emission (1 A). Furthermore, as the electron emission increased, the volt-ampere characteristic curve was shifted towards lower voltages. In a vacuum more than 10,000 volts would be required to obtain the saturation currents mentioned; actually, almost the whole characteristic was obtained at voltages below the lowest critical potential (5 volts). This might have two causes, oscillations or reverse fields.

For steady oscillations there must be a falling characteristic and the a.c. energy generated in the arc must compensate the a.c. energy lost in the external circuit; as the latter quantity is positive, the a.c. voltage and a.c. current in the generating arc must be in opposition (added to the d.c. components they give therefore a falling characteristic). The character of the oscillations depends upon the part of the characteristic where they are produced; there may be current variations at a nearly constant voltage, of small energy and difficult to maintain. Or there may be brief surges of current when the current is low, but when the voltage variations are so considerable that the potential falls below the lowest potential which can maintain the arc. Oscillations in the absence of reactance are only a special case of these latter oscillations; but then the applied voltage, E, must be above the ionization potential, v_i; the period being approximately $T = RC \ln\left[\frac{E - V_{cr}}{E - V_i}\right]$. The variety of conditions under which oscillations may or may not be produced is evident and accounts for the fact that different authors report different results.[1]

In most of the characteristics studied in the present work the conditions were unfavorable for oscillations; under these circumstances reverse fields or counter-electromotive forces [1] may account for the abnormal low-voltage arc. There is first a zone of ionization quite close to the filament, a strong ion concentration and then

[1] Illustrations of these different types may be found in several papers by K. T. Compton and K. Eckart.

a zone of diffusion where the motion of the electrons goes, regardless of the electric field, from the high concentration, n_2, to the lower concentration, n_1; such cases have been known for a long time in Geissler discharge tubes. The formula used for concentration cells in electrolytes may be applied and gives $V = Vo \ln \frac{n_1}{n_2}$. ($Vo$ corresponding to the average energy of electrons.) These reverse fields were studied by measuring the resistance of the discharge path to a high-frequency current, just as in an electrolyte. Then $E - e = ri$, e being the counter-electromotive force. The experiments brought out the existence of counter e.m.f's of from 0 to 10 volts in mercury. With low arc currents the a.c. and d.c. resistances were nearly the same; on the other hand, just before saturation was reached the h.f. resistance increased enormously to over ten times the d.c. value. This increase will be studied by using different frequencies.

Argon was found to increase the current markedly above a certain value. Absorption measurements of the $2p_3$ lines will give a measure of the number of $2p_3$ atoms; absorption measurements after the arc has been interrupted must furnish a value for the duration of the metastable state.

Italy to Draw More Power from Alpine Sources. (*Compressed Air Magazine*, Jan., 1926, p. 1498.)—Alpine glaciers and the heavy coverings of snow cloaking parts of those towering mountains will furnish motive power for two new hydro-electric plants having a combined capacity of 88,300 h.p. The falling waters emanating from the glaciers and the snow will drive the turbo-generators to be installed at Pallenzeno and Rovesca.

According to a news report, it will not be necessary to erect dams to impound the flow inasmuch as the melting goes on continuously and at a rate which will insure at all times an ample supply of water to drive the turbo-generators. Even though the minimum volume may not seem large, still the head available will always be a high one and provide sufficient energy to insure the steady development of more than 88,000 h.p.

The two new plants will be in the neighborhood of Lake Maggiore; and most of the work in connection with their development has been centred in driving a 17-mile tunnel through solid rock. This, of course, has necessitated much drilling and blasting. The Pallenzeno and Rovesca power-houses will be linked with the well-known Italian Edison superpower system which, with the new stations, will have a total generating capacity of 1,060,000 h.p.

NOTES FROM THE RESEARCH LABORATORY, EASTMAN KODAK COMPANY.*

THE PLASTICITY OF CELLULOSE IN CUPRAMMONIUM HYDROXIDE.[1]

By E. K. Carver and H. Folts.

THE Bingham and Green plastometer has been modified by allowing the liquid being measured to run into a chamber containing toluene. The volume of toluene displaced into a graduated side tube equals the volume of liquid that has passed through the capillary. By means of this instrument plasticity curves have been measured for various concentrations of cellulose in cuprammonium hydroxide. The logarithm of the apparent viscosity when plotted against concentrations gives nearly a straight line.

THE TIME FACTOR AND YIELD VALUE OF CELLULOSE ESTERS.[2]

By S. E. Sheppard, E. K. Carver, and S. S. Sweet.

FILMS of cellulose esters are not perfectly elastic, but have a definite rate of flow even under small loads. This rate of flow is proportional to a high power of the load, instead of being proportional to the difference between the load and yield value as is the case with some plastics. The yield value as determined by such machines as the Schopper paper tester depends on the rate at which the tester is run, and is equal to the load necessary to make the film stretch as fast as the pull is applied. By varying the time of the test from five seconds to eight hours, the yield value and the breaking load could be changed from 15 kilograms to 7 kilograms. The yield value is roughly proportional to the logarithm of the rate at which the machine is run.

* Communicated by the Director.

[1] Communication No. 226 from the Eastman Kodak Research Laboratory and published in *J. Amer. Chem. Soc.*, **47**: 1430, 1925.

[2] Communication No. 247 from the Research Laboratory of the Eastman Kodak Company and published in *Ind. Eng. Chem.*, **18**, 76, 1926.

Changes in the Density of Tungsten Caused by Working. W. GEISS and J. A. M. VAN LIEMPT. (*Ann. d. Phys.*, No. 5, 1925.)—Lorenz found that drawing tungsten into finer and finer wire reduced its density from 19.1 to 17.9. Schriever, on the other hand, claimed that the same process made the density rise from 19.13 to 20.26. So long as the density measured is smaller than the true density, an explanation for either of these two changes can be suggested. The increase in density may be due to the closing up of interstices between the small crystals, while diminution in density may be attributed to the formation of cracks in the metal.

From considerations based on X-ray behavior, Burger states the density of the metal to be 19.37. The authors of this paper used a single crystal and from it obtained the value 19.35. In their examination of the effect of working on density they were, no doubt, fortunate in carrying on their experiments in the laboratory of a lamp factory in Eindhoven, Holland. Their rough material was tungsten powder. This was strongly compressed, sintered at 1300° C., and then heated almost to the melting-point. The product was hammered. This caused a continuous growth of the density from 16.88 to 19.22. Drawing then prolonged the increase to $19.41 \pm .04$ and, finally, to $19.28 \pm .06$, that is, to about the density of a single crystal. It is interesting to note that the weighings for density had to be done in benzol, because water attacked the tungsten. G. F. S.

On the Nature of the Disturbance in the Second Medium in Total Reflection. C. V. RAMAN. (*Phil. Mag.*, Oct., 1925.)—In Professor Raman's laboratory in Calcutta, B. N. Chuckerbutti five years ago investigated an allied phenomenon. He let a pencil of highly monochromatic light pass into and through a glass prism in such manner that it emerged almost grazing the surface of the prism by which it made its exit. Diffraction patterns are seen through the observing telescope that receives the emergent beam. Reproductions of these Fraunhofer patterns are given. The important part of the present paper, however, lies in this, *viz.*, that these patterns continue to appear even when the angle, at which the ray in the glass strikes the final surface, is larger than the critical angle. By the crude theory under these conditions no light should emerge into the air but all should be totally reflected back into the glass. Photographs are shown displaying the diffraction patterns when the angle of incidence is just the critical angle and also when it is a little larger. A progressive change of form can easily be noted. There is thus final evidence that light does penetrate into the second medium when the angle of incidence is larger than the critical angle.

A mathematical explanation is given for the observed penetration and emphasis is laid on the incompatibility of the observed results with Sir Arthur Schuster's views relating to total reflection.

G. F. S.

NOTES FROM THE U. S. BUREAU OF CHEMISTRY.*

AUTOMATIC DEVICES FOR EXTRACTING ALKALOIDAL SOLUTIONS.[1]

II. APPLICATION TO NUX VOMICA AND BELLADONNA ALKALOIDS.

By Howard R. Watkins and Samuel Palkin.

[ABSTRACT.]

A DETAILED study was made of the application of automatic devices to liquid preparations of nux vomica and belladonna. The results of the experiments showed that under conditions of de-alcoholization and subsequent prolonged hot extraction, no ammonium sulphate is carried over to the alkaloid concentrate; that almost all of the alkaloid is extracted in the first thirty minutes; that, even with a decided variation in the conditions of experiment, the quantity of titratable alkaloids extracted is not affected; that, in the case of belladonna, at least, a slightly greater quantity of alkaloid can be extracted by means of the automatic devices than by means of a separatory funnel; and that, in view of the high efficiency already obtainable with the simple types (reported for nux vomica and belladonna), there would appear to be no practical advantage in using the more complicated apparatus for extracting nux vomica and belladonna alkaloids.

DUST CONTROL IN GRAIN ELEVATORS.[2]

A PRELIMINARY investigation undertaken by the Bureau of Chemistry to determine what effect dust-collecting systems in grain elevators have on the weight of grain showed a great discrepancy in the design and installation of the equipment used for this purpose. Accordingly office studies, field investigations, and laboratory experiments were undertaken to determine the best method of controlling the dust-explosion hazard in the grain elevating industry. Dust collection in grain elevators may not prevent explosions, but it will keep a small dust ignition from developing into

* Communicated by the Chief of the Bureau.

[1] Published in *J. Am. Pharm. Assoc.*, 14 (Dec., 1925) : 1099.

[2] Department of Agriculture Bulletin No. 1373.

a disastrous explosion. The new dust-collecting equipment designed and tested by the Bureau of Chemistry should meet all objections to the installation of such systems on the ground that they affect the weight of grain.

The Thermal Conductivity of Wires and Rods. T. BARRATT and R. M. WINTER. (*Ann. d. Phys.*, No. 9, 1925.)—Great ingenuity has been brought to bear upon the determination of thermal conductivity and the number of methods devised is accordingly large. Since the electric current has come in the last half-century to be used for the production of heat, it has become possible to measure more accurately than before the input of energy, while at the same time the determination of temperature by the resistance thermometer or by thermo-electric junctions has improved the precision of the reading of another element essential to the calculation of the conductivity.

The authors of this paper have solved the problem of measuring the conductivity of substances of which only small quantities are available. In addition, the method is unusual in that it is applicable to good as well as to poor conductors of heat, to platinum and also to ebonite. For silver a wire 1 mm. in diameter and 50 cm. in length sufficed, that is, about .39 of a cubic centimetre. The wire under experiment was furnished at one end with heat at a known rate and projected into a space kept at constant temperature. When a stationary condition has been attained, the thermal conductivity can be calculated provided we know, besides the dimensions of the wire, the following three quantities, the number of calories imparted to the wire in a second, the temperature of the hot end and the emissive power of the surface of the wire. The way in which the first of these was obtained speaks well for the resourcefulness of the investigators. With the wire in position the input of electrical energy into a heating arrangement was measured. Then the wire was removed and the input again determined under similar conditions. The excess of the first quantity of energy over the second gave the amount imparted to the wire. A platinum resistance thermometer enabled the temperature of the hot end of the wire to be got with readiness. The last of the three quantities, though not so accessible, could be measured. When the conductivities are calculated it is seen that in the case of every substance investigated there is a difference between the value for room temperature and that for 100° C. While the conductivities of platinum, sodium glass, red fibre, oak, mahogany and beech increase with rising temperature, the opposite change is seen to occur with gold, palladium, molybdenum and ebonite.

The largest value of the conductivities was that of gold at 17° C., .705 cal./cm. sec. degree, and the smallest was that of ebonite at 100° C., .000131 in the same units. G. F. S.

NOTES FROM THE U. S. BUREAU OF MINES, DEPARTMENT OF COMMERCE.*

INCOMPLETE COMBUSTION IN NATURAL-GAS HEATERS.

By G. W. Jones, W. P. Yant, and L. B. Berger.

MANY tests of natural-gas heaters for warming rooms in houses have been made by the Bureau of Mines to determine: (1) What types of heaters, as usually operated, give products of incomplete combustion; (2) why combustion is incomplete; and (3) how, by proper adjustment or change in design, the different types of heaters can be made safer and more efficient.

Not only is there a loss of efficiency and an increased consumption of gas when a heater gives off products of incomplete combustion, but these products consist largely of carbon monoxide (CO), an insidious and treacherous gas, which when present in an atmosphere in amounts as small as 0.15 per cent. will cause death. Health and safety require that more than 0.01 per cent. carbon monoxide should never be present in air to be breathed, because even this amount will render inert 15 to 20 per cent. of the oxygen-carrying capacity of the blood of a person exposed for several hours to such an atmosphere, and may in time lower his vitality so that he becomes more susceptible to disease. Furthermore, this gas can not ordinarily be detected by sight, taste, or smell, and dangerous quantities may be present in the atmosphere of a room without the occupants being aware.

In Ohio during the winter of 1922–1923 incomplete combustion products from house heaters caused more than 50 deaths and 100 asphyxiations. Numerous fatalities have occurred in other states.

The results of the bureau's tests are in brief as follows:

Every natural-gas heater tested would liberate carbon monoxide under certain operating conditions.

Products of incomplete combustion are due to one of the following: (1) The heater has not been designed by the manufacturers to give good combustion; (2) the heater is properly designed by the manufacturer to give good combustion at certain

* Communicated by the Director.

gas flows and gas pressures, but is not flexible enough to burn efficiently under widely varying gas flows and gas pressures; (3) the heater is properly designed by the manufacturer, and is very flexible in operation, but users can too easily change the adjustments, so that the primary air-gas ratio is reduced or the gas flow increased beyond the safe capacity of the heater.

Formation of incomplete combustion products is primarily caused by restricting the air supply to the burning gas either because of faulty construction of the heater or because adjustments are so made that enough oxygen does not reach the flame to give complete combustion. Further details are given in Technical Paper 362 of the Bureau of Mines, which was recently published.

CLEANING TESTS OF CENTRAL ILLINOIS COAL.

By Thomas Fraser and H. F. Yancey.

IN recent years higher freight rates have been largely responsible for a growing demand for cleaner coal, especially from outlying markets. So far as Illinois coal is concerned this demand comes for the most part from the northwest states. A condition more conducive to profitable washery operation is resulting, and is reviving the interest of Illinois operators in coal-cleaning processes. For this reason much of the Bureau of Mines experimental work on the beneficiation of the coals of the eastern and interior fields has been done in Illinois.

As an integral part of this experimental work, the bureau, in coöperation with certain Illinois operators, has studied the problem of cleaning the No. 6 coal mined in Central Illinois.

Raw screenings from this district generally carry 13 to 16 per cent. and occasionally up to 20 per cent. of ash. Specifically, therefore, the problem is to produce a dependably uniform washed coal product containing about 10 per cent. ash from a raw coal that averages probably between 14 and 15 per cent. ash but fluctuates between 13 and 20 per cent., and to obtain this reduction in ash content with not more than 20 per cent. shrinkage.

The results indicate that cleaning the screenings and nut-coal sizes is practicable at mines of this field working the No. 6 seam, and that a cleaned coal product containing 10 to 11 per cent. ash may be expected. This ash content is approximately that of the

average face sample, excluding all segregated impurities that it is practicable to pick out in cutting a face sample.

A fuller description of the tests will be found in Technical Paper 361 of the bureau.

SILICOSIS AMONG MINERS.

By R. R. Sayers.

SILICOSIS, or miners' phthisis, has been known to occur among miners in certain districts for centuries. This disease is found among metal miners in New Zealand, Australia, South Africa, Great Britain, and in many of the states of the United States. Silicosis is due to breathing very fine rock dust. Rock dust high in free silica is found to be most injurious.

Some physicians have thought that silica dust by its sharp-edged and needle-like particles injures the lung tissue mechanically. Another belief is that the silica, being soluble in water and weakly alkaline liquids, injures lung tissue by its poisonous action.

The rate of development of silicosis depends upon the character of the dust, the amount breathed, length of exposure, past illness (especially tuberculosis), and physical fitness of the men.

Among gold miners in South Africa the average length of exposure to silica dust before silicosis develops is seven and a half years, the shortest period of exposure for like results is two and a half years.

Silicosis is usually divided into three stages: The first shows symptoms and physical signs of damage to lung tissue caused by exposure to dust, but capacity for work is not impaired. The second stage shows definite signs of silicosis and capacity for work is impaired, although not seriously or permanently. The third stage shows that specific signs of silicosis are or have been present and the capacity for work has been seriously and permanently impaired by the disease.

The cardinal symptom of silicosis is shortness of breath, especially on exertion. The cardinal sign is diminished expansion of the chest. Both are slight in the early stages and increase gradually with development of the disease. Other symptoms and signs, as coughing, frequent colds, pains in the chest, and X-ray findings, are very important in making a diagnosis.

Men having silicosis are more susceptible to tuberculosis than normal men.

Men with silicosis can improve in suitable surroundings to recovery in the first stage, can improve materially in the second stage, and somewhat in the third stage.

Many methods for determining the amount of dust in the air are available. The sugar tube method, the konimeter, and the impinger are chiefly used in the mining industry in the United States.

The elimination of silicosis among miners depends on preventing the formation of dust by wet mining methods—wet drilling and wetting sides, roof and bottom, muck, and rock piles; the use of sprays and water blasts to lay the dust after blasting; good mechanical ventilation to replace dusty air with clean air; and physical examination of all miners before employment and periodically thereafter. All of these means of prevention must be practised to insure success.

Further information on this subject is given in Technical Paper 372 of the Bureau of Mines.

The Allotropy of Manganese. A. J. BRADLEY. (*Phil. Mag.*, Nov., 1925.)—In this paper we learn why it is that of all common metals manganese has been the only one whose crystal structure has not been determined. Young's photographs of the X-ray patterns given by this metal were incapable of simple interpretation. In the present investigation many samples of manganese were used to produce diffraction patterns with X-rays, but no two samples gave the same result nor did any produce the same pattern as that obtained by Young. A study of the photographs showed that in the whole group only three distinct series of lines are present. Of these one was obtained from electrolytic manganese only. "The other two series of lines occur on every specimen of commercial manganese from whatever source obtained and whatever the degree of purity of the sample or its method of manufacture. It is clear that we are dealing with mixtures of at least two allotropic modifications which are present in different proportions in every sample." To isolate the one from the other heat treatment was resorted to. For example, a certain specimen was photographed with X-rays at 120°, 150°, 300°, 400°, 500°, and 600°. At all these temperatures it gave the β lines only. At 670° and 750° both the β and γ lines were present, but at 905° only the latter lines appeared. The β form seems to be stable from 150° to 850° and the γ form from 650° upwards. Thus both may co-exist from 650° to 850°.

After this paper was sent in for publication a note was printed in *Zeitschrift für Physik*, by Westgren and Phragmen, announcing that they, too, had reached the conclusion that manganese has three allotropic forms. G. F. S.

THE FRANKLIN INSTITUTE.

(Proceedings of the Stated Annual Meeting, Wednesday, January 20, 1926.)

THE stated annual meeting of the Institute was called to order at eight-eighteen P.M. by President W. C. L. Eglin.

The Secretary stated that the minutes of the last meeting had been printed in full in the January number of the JOURNAL of the Institute and moved that those minutes be approved as printed. The motion was adopted unanimously.

The President called for a report of the Tellers appointed for the annual election. The Tellers were—Messrs. W. M. Stine, A. J. B. Harris and W. C. Schafer. For the Tellers, Doctor Schafer submitted the following report:

Total number of votes cast: 422 legal votes and 11 defective votes.

President: (to serve one year)	Wm. C. L. Eglin	421
Vice-president: (to serve three years)	C. C. Tutwiler	421
(to serve one year)	Walton Forstall	421
Treasurer: (to serve one year)	Benjamin Franklin	422
Managers: (to serve three years)	James Barnes	420
	George H. Benzon, Jr.	421
	G. H. Clamer	421
	Theobald F. Clark	420
	Arthur W. Goodspeed	420
	Charles Penrose	421
	George D. Rosengarten	421
	William Chattin Wetherill	420
(to serve two years)	F. J. Chesterman	421

The President then announced the election of the gentlemen for whom the reported votes had been cast.

The Secretary moved that a vote of thanks be extended to the three Tellers for their helpful service in conducting the election. The motion was adopted by unanimous vote.

On behalf of the Board of Managers the Secretary reported that since October 1, 1925, thirty-nine members had been elected to the Institute. He again called the attention of the Institute to the plan of the Board of Managers for a canvass for membership, and showed the literature which had been prepared by special committee for the purposes of this canvass. He stated that such literature would be constantly available for members who wished to make use of it.

The President then read his annual report which will be published in full in the Year Book of the Institute. He summarized the reports of the various Chairmen of the Committees having charge of the several activities of the Institute.

The President introduced as the speaker of the evening Dr. C. E. K. Mees, Director of the Research Laboratories of the Eastman Kodak Company. Doctor Mees spoke brilliantly on the topic, "The Color Sensitivity of Photo-

graphic Material." The lecture was followed by an animated discussion of the paper of the evening.

The meeting adjourned at nine-fifty P.M., with a hearty rising vote of thanks to Doctor Mees for his highly instructive and stimulating lecture.

HOWARD MCCLENAHAN,
Secretary.

COMMITTEE ON SCIENCE AND THE ARTS.

(Abstract of Proceedings of Stated Meeting held Wednesday, January 6, 1926.)

HALL OF THE COMMITTEE,
PHILADELPHIA, January 6, 1926.

MR. HAROLD CALVERT *in the Chair.*

The following reports were presented for first reading:

No. 2841: Linerite, A Rubber Lining for Ball Mills.

No. 2845 and No. 2846 } The Franklin Medal.

GEO. A. HOADLEY,
Secretary to Committee.

MEMBERSHIP NOTES.

ELECTIONS TO MEMBERSHIP.

(Stated Meeting, Board of Managers, January 13, 1926.)

RESIDENT MEMBERS.

MR. H. LINWOOD GODFREY, Patent Solicitor, Electrical Engineer, 32 South Broad Street, Philadelphia, Penna.

MR. DEXTER NICHOLS SHAW, Chemical Engineer and Patent Solicitor, 32 South Broad Street, Philadelphia, Penna.

DR. T. G. DELBRIDGE, Supervisor, Process Division, Atlantic Refining Company, Philadelphia, Penna.

NON-RESIDENT MEMBERS.

DR. FRED W. KRANZ, Research Physicist, Riverbank Laboratories, Geneva, Ill.

MR. FORREST WILLIAM MANKER, Vice-president, Surface Combustion Company, 366 Gerard Avenue, New York City, N. Y.

MR. CLEMENT B. NEWBOLD, JR., Student, Jenkintown, Penna. For Mailing: Princeton University, Princeton, N. J.

DR. CHARLES R. RICHARDS, President, Lehigh University, Bethlehem, Penna.

CHANGES OF ADDRESS.

MR. ONWARD BATES, 934 John's Road, Augusta, Ga.

MR. JOHN W. BROCK, 1607 Walnut Street, Philadelphia, Penna.

MR. ROBERT CRAIG, 42 Broadway, New York City, N. Y.

MR. ROLAND B. DAY, Room 842, 25 Broadway, New York City, N. Y.

MR. LEWIS M. DRAKE, 509 North First Street, Daytona Beach, Fla.

MR. SHERMAN M. FAIRCHILD, 898 Park Avenue, New York City, N. Y.
MR. CHARLES F. FORSTALL, Reading Company, Reading, Penna.
PROF. W. LASH MILLER, 8 Hawthorne Avene, Toronto 5, Canada.
MR. FREDERICK W. SALMON, P. O. Box 1392, Birmingham, Ala.

NECROLOGY.

John D. McIlhenny, Philadelphia, Penna.
Jacob Y. McConnell, Philadelphia, Penna.
George F. Ott, Philadelphia, Penna.

LIBRARY NOTES.

RECENT ADDITIONS.

American Association for the Advancement of Science.—Summarized Proceedings for the Period from June, 1921, to June, 1925. 1925.
BOHR, NIELS.—On the Application of the Quantum Theory to Atomic Structure: Part I. The Fundamental Postulates. 1924.
BRYANT, J. M., and CORRELL, J. A.—Alternating-current Circuits. 1925.
DE BRUYNE, N. A.—The Electrolytic Rectifier. 1924.
FOSTER, WM., and HEATH, H. W.—Laboratory Exercises in General Chemistry. 1925.
JACOBY, H. S., and DAVIS, R. P.—Foundations of Bridges and Buildings. 1925.
JÜPTNER, HANS VON.—Gas, Dampf und Flüssigkeit. 1925.
KEYNES, J. M.—A Treatise on Probability. 1921.
LEGENDRE, R.—La Concentration en Ions Hydrogène de l'Eau der Mer. 1925.
LUCKIESH, M., and PACINI, A. J.—Light and Health. 1926.
MORRELL, R. S., and WOOD, H. R.—The Chemistry of Drying Oils. 1925.
OTT, L. A.—Wassermessungen bei Wasserkraftanlagen. 1924.
RICHARDS, C. R.—The Industrial Museum. 1925.
Society of Chemical Industry.—Annual Reports of the Progress of Chemistry. Vols. 8 and 9. 1923–1924.
UNDERHILL, FRANK P.—The Lethal War Gases. 1920.
VANDERWALKER, F. N.—House Painting Methods with the Brush and Spray Gun. 1925.

BOOK REVIEWS.

LIGHT AND HEALTH. By M. Luckiesh and A. J. Pacini. viii–302 pages, illustrated, 8vo. Baltimore, The Williams and Wilkins Company, 1926. Price, $5.

The authors of this book are connected with research departments of the General Electric Company, the senior in the department of lighting and the junior in the biophysical department. Their extensive investigations in the field to which the book is devoted enable them to present a very comprehensive volume. It contains an immense amount of matter of the most interesting and practically valuable character. The literature of the subject, which is vast

and increasing with great rapidity, has been thoroughly searched and its essence presented. Naturally some, perhaps much, of the material offered of late will be found less trustworthy than supposed, but the general fact that the light of the open sky and the direct sunlight have a wonderful vivifying effect cannot be doubted. "All that a man hath will he give for his life," but it is too true that many men and women neglect the methods of preserving that life by proper conduct and by lack of keeping close to nature's heart.

It is becoming increasingly evident that we live too much indoors and rely too much upon artificial light and defective methods of heating. Our industrial civilization acts unfavorably upon our health, for our factories and railroads produce smoke which cuts out the beneficial rays from the sun and sky. Doubtless the enormous amount of canned goods that is now consumed has an unfavorable effect. It seems to be established that mere exposure to ultra-violet radiation will activate certain foods. Our glass windows cut out much of the beneficial rays, and it is to be hoped that research will soon give us a quartz glass or a transparent material of similar properties, that we may construct at reasonable cost sun parlors that will protect us from inclemency and yet give us almost all the benefit of the open.

Those who wish to learn what a vast amount of interesting information has already been obtained by patient and well-directed research will find this book of great value. Its errors are a diffuseness of style and a constant tendency to speculate on the origin of things and on the conditions of the universe in past ages. We know nothing about these matters and there is no use discussing them in a scientific work. The first sentence gives promise of caution in this respect, but the authors succumb to the temptation. They say, "How and when the earth was formed are conjectural matters and the same is true of the dawn of life upon this planet. These fascinating subjects have tempted the imaginations of thinking men of all ages, but let us avoid this temptation and begin with the fairly certain knowledge that the earth was bathed in sunlight when the first primitive cells of living matter came into existence." The paragraph shows the two errors above noted, "first primitive" is useless tautology, and no one knows what was the condition of the earth when the first living cells originated.

Some eccentricities of spelling are noted. "Brunette" is spelled "brunet," but "blonde" retains its "e." The name of the unit of wave-length is always spelled without either umlaut. By a slip "Priestley" loses the second "e."

HENRY LEFFMANN.

LABORATORY EXERCISES IN GENERAL CHEMISTRY. By William Foster, A.M., Ph.D., Princeton University, and Harley Willis Heath, B.S., Lawrenceville School. 186 pages, small 8vo, illustrated. New York, D. Van Nostrand Company, 1925. Price, $1.25.

No laboratory manual will serve two masters, except they are joined in its production as in this case. The details of teaching of general chemistry to young persons are so complicated that each teacher finds special methods needed. The book in hand is written as a companion to a text-book by the senior author and, therefore, in a specialized form. It comprehends the standard

experiments for elementary instruction and a detailed discussion of its text is not needed. Doubtless other teachers than the authors would suggest amendments, but these would not materially change the form of the book. The large classes that are now receiving instruction in chemistry in American institutions necessarily bring into prominence many who are not well adapted to the study, lacking the neatness, patience and mechanical aptitude that such work requires. A walk through most students' laboratories will show many instances of neglect of precautions or of rules: Bunsen burners with too much air, filters too large for the funnel, filter stems not touching the beaker wall but the filtrate allowed to splash as it falls. When the delicate analytical balance is used, serious neglect is often noted.

The reviewer notes as an omission in the present book that while in describing the use of the cork-borer the stout rod that is always with the set is advised for use in pushing out the plug of cork, no mention is made of its convenience as a cross-bar in operating the borer. HENRY LEFFMANN.

GAS, DAMPF UND FLÜSSIGKEIT. By Hofrath Professor Ing. Hans von Jüptner. Pamphlet, 61 pages, 8vo. Leipzig, Otto Spamer, 1925. Price, bound, 5 marks.

This is fasciculus 8 of a series entitled "Monographien zur Feuerungstechnik," being an enlarged reprint from a periodical devoted to the general subject. Gases and vapors show departures from the law which is usually known in Great Britain as that of Boyle and on the continent, especially in France, as that of Mariotte. In this pamphlet the law is ascribed to Gay-Lussac and Mariotte. The essay is a study of the physics of gases, vapors and liquids, several different substances being comprehended, and very elaborate experimental methods applied. The data obtained are presented in numerous tables and the mathematical problems involved are set forth in detail.

HENRY LEFFMANN.

LA CONCENTRATION EN IONS HYDROGÈNE DE L'EAU DE MER. By R. Legendre, College of France at Concarneau. viii–283 pages, 30 illustrations, 8vo. Paris, University Presses of France, 1925. Price, 30 francs.

This is a volume of a series "Biologic Problems," which is a collection of treatises dealing with present-day questions and intended to give to laboratory workers data concerning the most recent progress expressed in concise form. Writing for the workers in biologic laboratories, the author has set forth with clearness and simplicity the general physical and chemical phenomena observed in liquids, and the mechanism of chemical reactions, comprehending both solutions found in nature, such as fresh and salt waters, and those produced in living organisms. The first section of the book instructs in the nature of hydrogen-ion concentration and the methods for its determination. It is gratifying to note that the symbol pH is used. There has been much irregularity in this respect, but Sörensen's original form is extremely inconvenient and it is fortunate that it has found little favor.

The second part of the book is a coördinated, systematic presentation of the great mass of problems that have been developed and studied of recent years concerning the relation of pH to biologic phenomena. Many problems of geology and geophysics are involved in these investigations and the book is a comprehensive and detailed discussion of these. There is a good index.

HENRY LEFFMANN.

ALLEN'S COMMERCIAL ORGANIC ANALYSIS. Vol. iv, fifth edition, entirely rewritten. Edited by Samuel S. Sadtler, B.S., Elbert C. Lathrop, A.B., Ph.D., and C. Ainsworth Mitchell, M.A., F.I.C., assisted by collaborators. x–648 pages, 8vo. Philadelphia, P. Blakiston's Son and Company, 1925. Price, $7.50.

The new Allen comes on apace and chemists everywhere will welcome the volumes. The present reviewer remembers vividly the interest aroused when the first edition of the work was put out more than half a century ago. The originator has long since passed away, but his system and manner of treating the topics comprised in the work are still exhibited. The intervening time has wrought tremendous changes in the scope and routine of the commercial organic analysis. The active control of the work has been made a joint service of the two great English-speaking countries and the literatures of all nations contributing to the development of chemistry have been drawn upon.

The present volume includes the complex hydrocarbons of natural origin, resins, essential oils, rubber, gutta percha and allied substance. One might speak of the rubber section in a slight modification of what Mr. Pickwick said to Count Smaltork, substituting "rubber" for "politics." "The word rubber comprises in itself a difficult study of no inconsiderable magnitude," having special reference to the present international situation, for rubber is looming alongside of oil and coffee as *casus belli*. The subject has grown into immense importance as everyone knows. Mr. John B. Tuttle has contributed the section. E. K. Nelson and G. A. Russell present the special characters of essential oils, Ernest J. Parry the chapters on resins and constituents of essential oils and allied substances. The volume is full of most valuable information and will be an indispensable feature of the working laboratory.

HENRY LEFFMANN.

THE BUREAU OF STANDARDS. ITS HISTORY, ACTIVITIES, AND ORGANIZATION. By Gustavus A. Weber. Institute for Government Research, Service Monographs No. 35. xv–298 pages, 8vo. Baltimore, The Johns Hopkins Press, 1925. Price, $2.

This is a publication of the series being issued by the Institute for Government Research, an association of citizens for coöperating with government officials for the scientific study of the departments with a view to increasing efficiency and affording the public at large opportunity to learn of the methods and purposes of the several departments and the results accomplished. Present-day governments are extremely complex in organization, and among the features that are least in direct contact with the public at large are the scientific bureaus.

some of which, indeed, like the Bureau of Standards which is the special subject of this volume, are scarcely known outside of the circle of specialists who depend on the work of the bureau. The Bureau of Standards has been functioning for many years and giving most valuable aid. The setting forth of its main historical features, its present organization and its activities in the many lines with which it has been concerned is a timely contribution to the literature of the Institute for Government Research. HENRY LEFFMANN.

THE ALKALI INDUSTRY. By J. R. Partington, D.Sc., University of London. Second edition, xii–344 pages, illustrated, 8vo. New York, D. Van Nostrand Company, 1925. Price, $4.

This work is a comprehensive presentation of the processes in use in the manufacture of what are commonly called "heavy chemicals." It comprises much more than the title indicates, for the salt, sulphuric acid, chlorine and nitric acid manufactures are given full description. These substances are, indeed, so intimately connected with the production of alkalies that it is practically impossible in a technical work to exclude them. In connection with each specific description some instructive data are given concerning the beginning of the industry, enabling the reader to appreciate the contrast that exists between chemical engineering then and now. One of the changes most influential in modifying the methods of chemical industry has been the economic production of electricity. Electrolytic methods have taken the place of many standard procedures of the last century. With the development of water-power and cheaper fuels, which latter advance it is devoutly to be hoped will come soon, still further application of electricity will be possible.

The work gives in much detail the several processes now recognized as best for the manufacture of the chemicals used in great quantity. Considerable information is given concerning the methods of obtaining ammonia, the Haber process being duly described, but the catalyst used seems to be not definitely known. The contact process for sulphuric acid has an instructive history. Davy first noted that platinum will cause a union of sulphur dioxide and oxygen, but the fact remained for many years unapplied. A British experimenter developed the principle, but his operation was not successful because the impurities in the gases soon destroyed the activity of the platinum. This effect, which is now often called the "poisoning of the catalyst," is caused largely by arsenic and mercury. Advance of the contact method to complete success has been due largely to the researches of chemists under the auspices of two German firms. These workers perfected treatments by which the impurities can be entirely removed.

While American work is frequently noted, the book is written principally from the British standpoint. This does not constitute a serious drawback, because of late years great advances in chemical industries have been made in England. The war brought home to many nations the value of the equal cultivation of theory and practice and the importance of research in all lines. The book is liberally illustrated with line drawings which aid materially in the understanding of the procedures. HENRY LEFFMANN.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS. Report No. 221, Model Tests with a Systematic Series of Twenty-seven Wing Sections at Full Reynolds Number. By Max M. Munk and Elton W. Miller. 18 pages, illustrations, quarto. Washington, Government Printing Office, 1925. Price, ten cents.

A systematic series of twenty-seven wing sections, characterized by a small travel of the centre of pressure, have been investigated at 20 atmospheres pressure in the variable density wind-tunnel of the National Advisory Committee for Aeronautics.

The results are consistent with each other, and indicate that for such "stable" sections a small effective camber, a small effective S-shape and a thickness of 8 to 12 per cent. lead to good aerodynamic properties.

Report No. 232, Fuels for High-compression Engines. By Stanwood W. Sparrow. 20 pages, illustrations, quarto. Washington, Government Printing Office, 1925. Price, ten cents.

This report is based very largely on results of tests made at the Bureau of Standards during 1922, 1923, and 1924, under research authorization of the National Advisory Committee for Aeronautics.

From theoretical considerations one would expect an increase in power and thermal efficiency to result from increasing the compression ratio of an internal-combustion engine. In reality it is upon the expansion ratio that the power and thermal efficiency depend, but, since in conventional engines this is equal to the compression ratio, it is generally understood that a change in one ratio is accompanied by an equal change in the other. Tests over a wide range of compression ratios (extending to ratios as high as 14:1) have shown that ordinarily an increase in power and thermal efficiency is obtained as expected provided serious detonation or pre-ignition does not result from the increase in ratio.

There are marked differences between fuels as regards the conditions under which they detonate or pre-ignite. It follows that the employment of a high-compression ratio is contingent upon securing a fuel which is suitable in its resistance to pre-ignition and detonation, and which at the same time possesses the other qualities essential to a satisfactory engine fuel.

This report emphasizes the fact that there may be a difference between a fuel's ability to resist detonation and its ability to resist pre-ignition. Although this report is primarily a general discussion of the properties essential to a satisfactory fuel for high-compression engines, certain fuels, benzol and alcohol in particular, are discussed in some detail.

PUBLICATIONS RECEIVED.

Light and Health: A discussion of light and other radiations in relation to life and to health by M. Luckiesh and A. J. Pacini. 302 pages, illustrations, 8vo. Baltimore, The Williams and Wilkins Company, 1926. Price, $5.

Helmholtz's Treatise on Physiological Optics: Translated from the third German edition. Edited by James P. C. Southall, Professor of Physics in Columbia University. Vol. III, The Perceptions of Vision. 736 pages, illus-

trations, plates, 8vo. Ithaca, New York, The Optical Society of America, 1925. Price, $7.

Draft and Capacity of Chimneys, by J. G. Mingle, C.E. 339 pages, illustrations, 12mo. New York, D. Van Nostrand Company, 1925. Price, $3.50.

The Mystery of the Mind, by Leonard T. Troland, S.B., A.M., Ph.D., Assistant Professor of Psychology, Harvard University. 253 pages, illustrations, 12mo. New York, D. Van Nostrand Company, 1926. Price, $3.

The Chemical Analysis of Foods: A practical treatise on the examination of foodstuffs and the detection of adulterants, by Henry Edward Cox, M.S., Ph.D., F.I.C. 323 pages, illustrations, 12mo. Philadelphia, P. Blakiston's Son and Company, 1926. Price, $5.

Memoranda of Toxicology Partly Based on Tanner's Memoranda of Poisons, by Max Trumper, B.S., A.M., with introduction and addenda by Henry Leffmann, A.M., M.D. 230 pages, 16mo. Philadelphia, P. Blakiston's Son and Company, 1925. Price, $1.50.

The Department of the Interior: A Review for 1925, by Hubert Work, Secretary of the Interior. 39 pages, illustrations, 8vo. Washington, Government Printing Office, 1925.

U. S. Bureau of Standards: Technologic Papers, No. 297, A Statistical Study of Conditions Affecting the Distance Range of Radio Telephone Broadcasting Stations, by C. M. Jansky, Jr. 10 pages, illustrations, 8vo. Washington, Government Printing Office, 1925. Price, five cents.

U. S. Bureau of Mines: Slate in 1924, by G. F. Loughlin and A. T. Coons. Mineral Resources of the United States, 1924, Part II. 10 pages, 8vo. Washington, Government Printing Office, 1925. Price, five cents.

Sound-absorbent Plaster Invented. (The Science News Letter, No. 249.)—In response to the assertion of a prominent hospital official that "noise is the curse of modern hospital construction" comes the invention of a "sound-absorbing" plaster which is from eight to ten times as absorbent of sound as the ordinary plaster, according to actual tests by its inventor, Dr. Paul E. Sabine, of the Riverbank laboratories near Chicago.

"Modern buildings of solid construction with smooth, hard surfaces make the present-day interior an almost perfect reflector of sound," said the inventor. "Proper sanitation and satisfactory acoustics are apparently mutually antagonistic requirements.

"Ordinary masonry walls are much better reflectors of sound than the best mirrors are of light. The best mirrors reflect about 90 per cent. of their light energy, but a tile wall with hard plaster reflects more than 97 per cent. of the sound energy which strikes it. From such walls it can be shown that a sound initially of ordinary intensity must undergo some 450 reflections before it is absorbed so as to be inaudible. A simple computation shows that the sound remains in the room for 4.8 seconds before it is absorbed.

"If a carpet is put on the floor it absorbs 25 per cent. of the sound energy which strikes it, and reflects 75 per cent. Instead of 450

reflections as above, we now have 144 reflections requiring 1.5 seconds to become inaudible. But sanitary conditions in a hospital bar carpets, draperies, and other sound-absorbing apparatus. The ideal solution of the problem lies in the wall surfaces of the room," the investigator continued.

As a practical demonstration of the sound-absorbing qualities of the new plaster, the physicist has plastered two rooms, one with the ordinary plaster, and the other with a thickness of one-half inch of the absorbing plaster. The difference in the acoustics of the two rooms is pronounced. In the first there is a reverberation of sound for several seconds, and in the second, all sound is "dead."

A small portable pipe organ, arranged to speak at a constant wind pressure, is used as a source of varying the pitch. This has with it a specially designed chronometer for measuring the duration of audible sound.

The collected data show that the absorbing efficiency of the plaster is much greater for tones that are higher than 512 vibrations per second, which is, said the physicist, similar to the crying of patients in pain, or of infants, in the upper range of the pitch scale. The material seems to be particularly fitted for the walls of hospitals.

"The acoustical properties of the plaster depend upon its porosity. Its surface, texture, and hardness is that of other rough finish plasters," he said. "A new paint has also been invented to go with the plaster."

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